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KADI

A design study of a pan-African climate observation research infrastructure

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1 Executive Summary

The KADI (Knowledge and Climate Services from an African Observation and Data Research Infrastructure) project aims to provide essential design considerations for a comprehensive network of sustainable pan-African research infrastructures (RI) to support climate services in Africa. Given the growing challenges of climate change, land degradation, and extreme weather events, there is an urgent need for long-term, coordinated observation networks across Africa. The KADI initiative addresses this need by proposing a multi-thematic research infrastructure that integrates carbon observation, atmospheric composition, biodiversity, earth system modelling, and coastal biogeochemistry. These research infrastructures will enhance Africa's capacity to monitor, analyse, and respond to climate and environmental changes effectively.

Long-term environmental research and observation infrastructures are essential for identifying trends, predicting risks, and guiding policy decisions. However, Africa’s observational networks are underdeveloped, limiting the continent’s ability to contribute to global climate science and mitigation strategies. To bridge this gap, the KADI project emphasizes the following key priorities:

1. **Sustainability:** Establishing long-term funding mechanisms through partnerships with national governments, continental bodies (e.g., African Union, UNECA), and international organizations.
2. **Expanded Observation Coverage:** Strengthening data collection across spatial and temporal scales, prioritizing critical climate variables such as greenhouse gases, air quality indices, extreme weather events, and biodiversity indicators.
3. **Data Integration:** Merging in-situ observations with Earth observation data to improve the accuracy and validation of climate models.
4. **Stakeholder Engagement:** Creating a Community of Practice that involves scientists, policymakers, and local communities to co-develop climate services and ensure practical implementation.
5. **Standardization and Open Science:** Promoting interoperability through globally recognized frameworks such as WMO GBON and FAIR data principles to enhance accessibility and transparency.
6. **Emerging Technologies:** Utilizing AI, remote sensing, and digital infrastructures for enhanced data analysis and decision-making capabilities.
7. **Capacity Building:** Investing in training programs, academic partnerships, and technical skill development to ensure long-term expertise in climate research and data management.

By establishing a coordinated, inclusive, and technology-driven research infrastructure, the KADI project will support evidence-based policymaking, sustainable resource management, and resilience-building for African ecosystems and communities. Additionally, it will strengthen Africa’s role in international climate negotiations by providing robust data on greenhouse gas emissions, biodiversity changes, and environmental stressors.

The successful implementation of KADI's proposed research infrastructures will not only address critical gaps in Africa's climate observation capabilities but also foster interdisciplinary collaboration and knowledge exchange. Ultimately, this initiative will enhance Africa's access to climate services which will enhance the capacity to respond to climate change, safeguard its natural resources, and contribute to global climate resilience efforts.

KADI

II. ACRONYMS

AOD:	Aerosol Optical Depth
CBD:	Convention on Biological Diversity
CCL:	Central Calibration Laboratories
EBVs:	Essential Biodiversity Variables
ECVs:	Essential Climate Variables
EOVs:	Essential Ocean Variables
ERI:	Ecosystem Research Infrastructure
ESM:	Earth System Modelling
ET:	EvapoTranspiration
FAIR:	Findable Accessible Interoperable Reusable
GAW:	Global Atmosphere Watch
GCOS:	Global Climate Observing System
GERI:	Global Ecosystem Research Infrastructure
GHG:	Green House Gases
ICOS:	Integrated Carbon Observation System
ILTER:	International Long-Term Ecological Research
INDAAF:	International Network to study Deposition and Atmospheric Chemistry in Africa
Debits Network	Deposition Network of the GAW
IoT:	Internet of Things
KADI:	Knowledge and climate services from an African observation and Data research Infrastructure
LTER:	Long-Term Ecological Research
LTSER:	Long-Term Socio-Ecological Research
MODIS:	Moderate Resolution Imaging Spectroradiometer
NEE:	Net Ecosystem Exchange
OSCAR:	Observing Systems Capability Analysis and Review Systems Tool
PMERL:	Participatory Monitoring Evaluation Reflection Learning
QA/SAC:	Quality Assurance or Science Activities Centres
RI:	Research Infrastructure
SMCRI:	Shallow Marine and Coastal Research Infrastructure
UN:	United Nations
UNFCCC:	United Nations Framework Convention on Climate Change
WDC:	World Data Centres
WMO:	World Meteorological Organization

III. Contents

CONTENTS

1 Introduction

Systematic long-term research and observations, are essential pillars of scientific inquiry, providing invaluable insights into trends, patterns, and changes that unfold over extended periods, these underpin our understanding of global change challenges at local, regional and planetary scales (Kulmala et al. 2023). Research Infrastructures and Observation Infrastructures to support climate services is vital for understanding complex phenomena such as desertification, land degradation, climate change, and episodic events such as droughts and floods which cannot be studied over a short period of time (Carbutt and Thompson 2021). These processes occur across various temporal cycles and cannot be studied and understood over a short period of time (Carbutt and Thompson 2021). By collecting data and monitoring variables over years or even decades, researchers can identify subtle shifts, emerging risks, and long-term impacts that would otherwise remain undetected. Therefore, it is imperative that researchers establish and maintain high-quality, long-term collaborative, and multi-disciplinary research networks aimed at understanding drivers and patterns of environmental change in a coordinated and multi-site approach (Mirtl et al. 2018). The existing observation networks in the southern hemisphere have a much narrower scope and a shorter history than regions north of the equator, with a particular lack of observations in Africa and the developing world. This calls for the coordinated establishment of an optimised and sustainable observation network in the African region to support local, regional and global long-term environmental research (Midgley, Chown, and Kgope 2007). Specifically, such a long-term observation network should be the foundation that drives collaborative and inclusive ecosystem, critical zone and socio- ecological research, balance the requirements of the research community and stakeholders (Mirtl et al., 2018) and support the delivery of climate services in the broadest terms. This approach is therefore critical for informing policy, guiding resource management, and addressing the challenges posed by dynamic and evolving systems. Moreover, as long-term observation and research networks advance the alignment and harmonization of data acquisition and methodologies and provides the fundamental knowledge required for sustainable development.

The aim of this deliverable is to provide a comprehensive compilation of envisaged observational networks related to challenges and climate services as defined in the output of Work Package 1.

The structure for the concepts of the research infrastructures to address the various elements of the suite of Research infrastructures to support Climate Services in Africa draws from the Key Elements for a Climate services infrastructure (**Error! Reference source not found.**), as defined in WP1 of the KADI project This consists of 6 major elements including;

- The foundational characteristics
- The governance and compliance for the infrastructure
- The types of observations and data sources,
- The data management, analysis and use of the data in modelling
- Building the skills and managing the knowledge that has been developed, and

- Developing and facilitating the collaboration networks

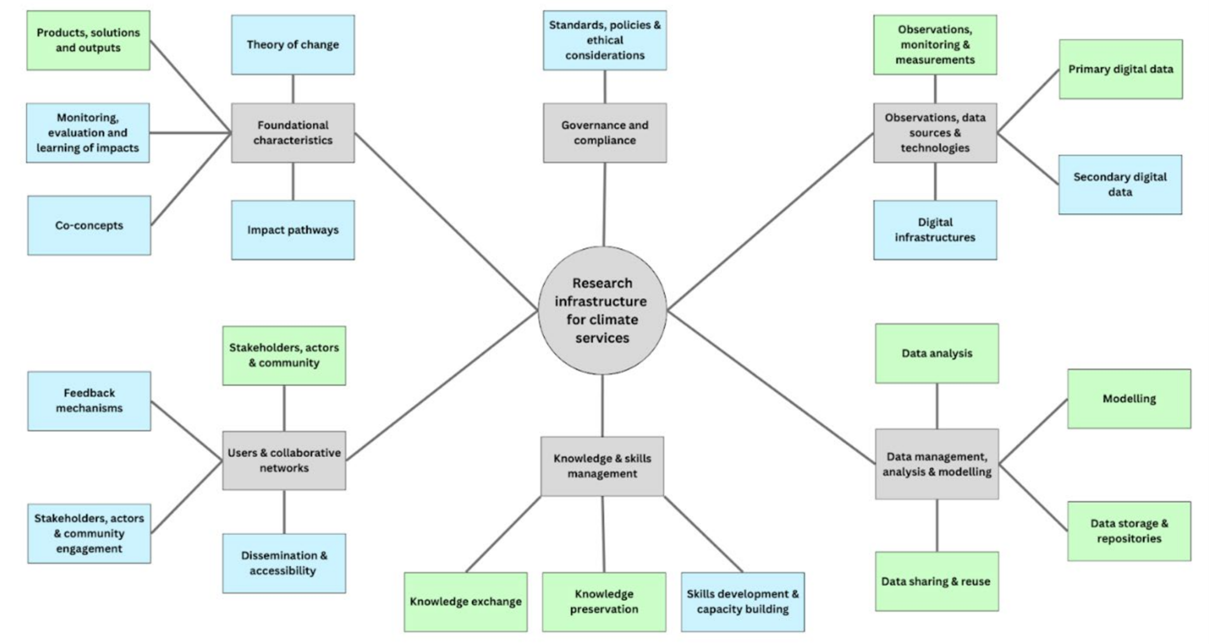

Figure 1 Key elements of a Research Infrastructure providing climate services. Green boxes indicate those elements that are typical in an RI and the blue boxes indicate those elements that are added through KADI WP1 work

As the WP1 concluded its stakeholder engagement activities in this project several recommendations for the design of a unified Pan African Climate Observation Research infrastructure were developed. These recommendations are addressed in the design of the research infrastructures as far as possible these elements have been addressed in the following discussion .

1.1 Recommendation: Elements of sustainability

- Identify which of the **operational elements of the RI - such as observation networks and other data acquisition processes - most critically require continuous funding for sustainability** (avoiding short term project-based funding).
- Suggest **possible organisations or sectors** that would be ideal RI funders, operators, and financial partners, and **what type of complementary roles** these organisations could have in securing the operational RI in the long run. Consider actors such as:
  - National meteorological and hydrological services (e.g. running local operations)
  - Research institutes and universities (e.g. personnel)
  - Continental organisations (e.g. large investments, capacity enhancement)
    - African Union Commission
    - The United Nations Economic Commission for Africa (UNECA)
    - African Development Bank (AfDB)
  - The Continental African Centre of Meteorological Application for Development (ACMAD)
  - Multi-national and international organisations (e.g. large investments)
  - Private businesses (e.g. providing climate services)
  - NGOs and possible grass-root level organisations (e.g. local personnel, local security, maintenance, local CS co-creation)

1.2 Recommendation: Improving the Spatial and Temporal coverage of the Observations

- Identify **the most critical observational data gaps** to reach **sufficient geographical coverage of the observations** at different spatial scales. Based on identified actors' needs, prioritise e.g. the following recurring themes:
  - Greenhouse gases (GHGs), short-lived climate forcers (SLCFs), air quality indices, extreme weather events, surface rainfall and temperatures, ocean circulation, and biodiversity-related parameters
- Suggest an **overall design of the spatio-temporal observation network**
  - At various spatial scales: Across the continent, within critical bio-climatic regions, and within local scales, such as cities (coverage, density, stationarity versus mobility)
  - Over time: Temporal frequency of measurements, longevity of the measurements
- **Leverage existing GHG and other climate related measurement networks and observation locations** into the RI design and thus maximise the benefits for all.

1.3 Recommendation: Complementarities between in-situ observations and earth observation and modelling data

- Provide concrete design applications on **how to combine high-precision measurements and observations (e.g. EC towers) with a deployment of low-cost tools and other alternative data acquisition methods** to address scalability and transfer of observations, such as:
  - Low-cost stationary sensors
  - Citizen sensing and participatory based approaches
  - Mobile phones with sensors and dynamic observation networks
- Envision **how the in-situ observations can be enriched and complemented by Earth observation data, and vice versa** (e.g. ground-truth validation)**,** including linkages to existing geospatial digital infrastructures, which are open-access and provide contextual data for GHG and other climate variable measurements, such as:
  - Copernicus, NASA, USGS data services
  - Google and other commercial services, with open access for research
  - Data cubes in Africa (e.g. Africa Regional Data Cube)

1.4 Recommendation: Actor Engagement and the development of a community of practice

- Suggest **concrete ways for researchers' and actors' engagement** for sustainable management and utilisation of the research infrastructure, including for example:
- Role of formal institutions (e.g., ministries, NMHSs, universities) in establishing, maintaining, using and benefiting from the RI and observation infrastructures, and their expected responsibilities. Leverage e.g. the idea of Regional Hubs.
  - Leverage and maintain existing relationships and well-functioning engagement practices between science and public domains for knowledge exchange, dialogue and mutual benefit.
  - Integrate local communities/volunteers/citizen scientists to practical operations of the RI, such as in data collection, validation, curation or management.
- **Establish a Community of Practice (CoP)**: a network of scientists, practitioners and residents/volunteers for the RI knowledge exchange, transfer, refinement, mutual learning and co-creation of the CSs, with common goals and a regular agenda for community activities. Include e.g. the following:

  - Establish open communication channels to encourage an iterative process of continued participation for the flow of knowledge, capacity building, and continuous identification of data, knowledge, and climate service needs.
  - Ensure representativeness of all actors, including researchers, funding agencies, government bodies, community groups, and industry partners across geographical scales of infrastructure engagement and sectors.
  - Work with and learn from local actors when e.g. establishing new physical observation stations, planning modes of delivery for climate services, and designing other RI operations to minimise disruption and maximise mutual benefit.

1.5 Recommendation: Standardised and interoperable RI Data and Practices

- Identify the most critical **commonly agreed standards for the RI to follow, enforce and further develop, that assist in the co-production of harmonized, compatible and interoperable** climate data and services
  - Data-specific standards for collection, management, sharing with a view of creating a “data space”
  - Open Science and FAIR data principles
  - WMO Global Basic Observing Network (GBON) standards
  - Global Framework for Climate Services, locally contextualised
  - Standard impact monitoring and feedback systems
  - Standards and guidelines for using emerging technologies (e.g. low-cost and mobile sensors) for data collection
- Establish **harmonised, ethical, and inclusive co-creation processes and other operational RI practices** across spatial scales that leverages good existing practices and considers local social and cultural uniqueness. Cover e.g. the following:
  - Establish and follow guidelines to recognise power asymmetries in actor engagement
  - Choose and develop best practices and methodologies for knowledge creation and exchange
  - Adapt international frameworks to local contexts
  - Establish standard approaches for monitoring and evaluating social, economic and environmental impact of the RI
  - Ethically integrate traditional, indigenous and local knowledge systems into RI operations
  - Apply existing good practices for co-production of climate services, such as the ‘Co-production of African weather and climate services’ manual by Future Climate for Africa and WISER (https://futureclimateafrica.org/coproduction-manual/)

1.6 Recommendation: Role of Emerging and New Technologies and Digital Infrastructures

- Identify how RI utilises, promotes, and provides access to **advanced digital research infrastructures and state-of-the-art digital tools** for climate data acquisition, management, processing, analysis and delivery in Africa, including for example:
  - Unmanned Aerial Vehicles (UAVs) Drones/mobile sensing
  - ML/AI
  - Supercomputers
  - Cloud environments
  - Virtual servers
  - Web services and APIs

    - Specialized databases
    - Social media
    - Energy requirements and the importance of off-grid power supply as needed
- Ensure **responsible and sustainable integration of emerging and new technologies in the RI operations** by identifying and managing risks and barriers, and by strategically enforcing digital sustainability of the RI in Africa.
    - Develop strategies to address barriers such as consistent uninterrupted electricity, internet connectivity, digital literacy and affordability for equitable access
    - Mitigate risks related to misinformation and skewed information (e.g. in AI) and data governance ("gatekeeping")
    - Encourage localization of emerging technologies to answer community needs, and co-design technical solutions with local actors
    - Advocate open and interoperable digital technologies and infrastructures that enable collaboration and advances just digital transformation

1.7 Training and Competence Growth

- Suggest how the **training and skills & competence development** of the researchers is organised within the RI ecosystem, what is the role of higher education institutes, and how needed knowledge and skills are also transferred to decision-makers and other actors. For example:
    - Integrating knowledge exchange to relevant higher education institutes, technical training colleges and wider research performing organisations' curricula and other learning opportunities for example via researchers associated with operational domain of the RI
    - Open online and/or live training workshops for anyone, related to e.g. maintaining observation instruments, data management in cloud environments, data access and further usage
    - Internship, employment or learning opportunities for young researchers, students and practitioners to actively engage in RI activities to ensure knowledge development of the next generation
- Partnering with global initiatives, international agencies, and funders for providing capacity enhancement opportunities within and across RI domains (e.g. data acquisition, analysis, usage of new technologies, co-creation practices, and policy). Leverage the Community of Practice and/or Regional Hubs in these partnerships.

KADI

2 Concepts for Pan African research infrastructures

This report demonstrates the requirements for a variety of scientific platforms, or Research Infrastructures (RI) on the African continent to support the provision of climate services. In this concept phase, the primary requirements for a RI are outlined, however the operations, funding and fine-scale locations of the RIs will not be discussed as this will depend heavily on the potential funding for the implementation of these RIs. Secondly, the RIs presented here are grouped according to their topic or process, and it is intended that significant interaction between the research infrastructures will be required to develop an integrated and holistic understanding of the social/environment/climate system.

The KADI project has developed from and is building off knowledge developed during the European Commission SEACRIFOG Project. One of the primary outputs of that project was the identification of an expanded list of essential climate variables (Lopez-Ballesteros et al. 2018) that would be needed to support climate services on the African Continent (**Error! Reference source not found.**) and this forms the basis for the development of the required RIs in this project. In the López-Ballesteros et al. (2018) study the Essential Variables were collected from the GCOS Essential Climate Variables, the GOOS Essential Ocean Variables, the IPBES Essential Biodiversity variables, anthropogenic factors and other variables some of which were identified as Essential for GHG observations (**Error! Reference source not found.**).

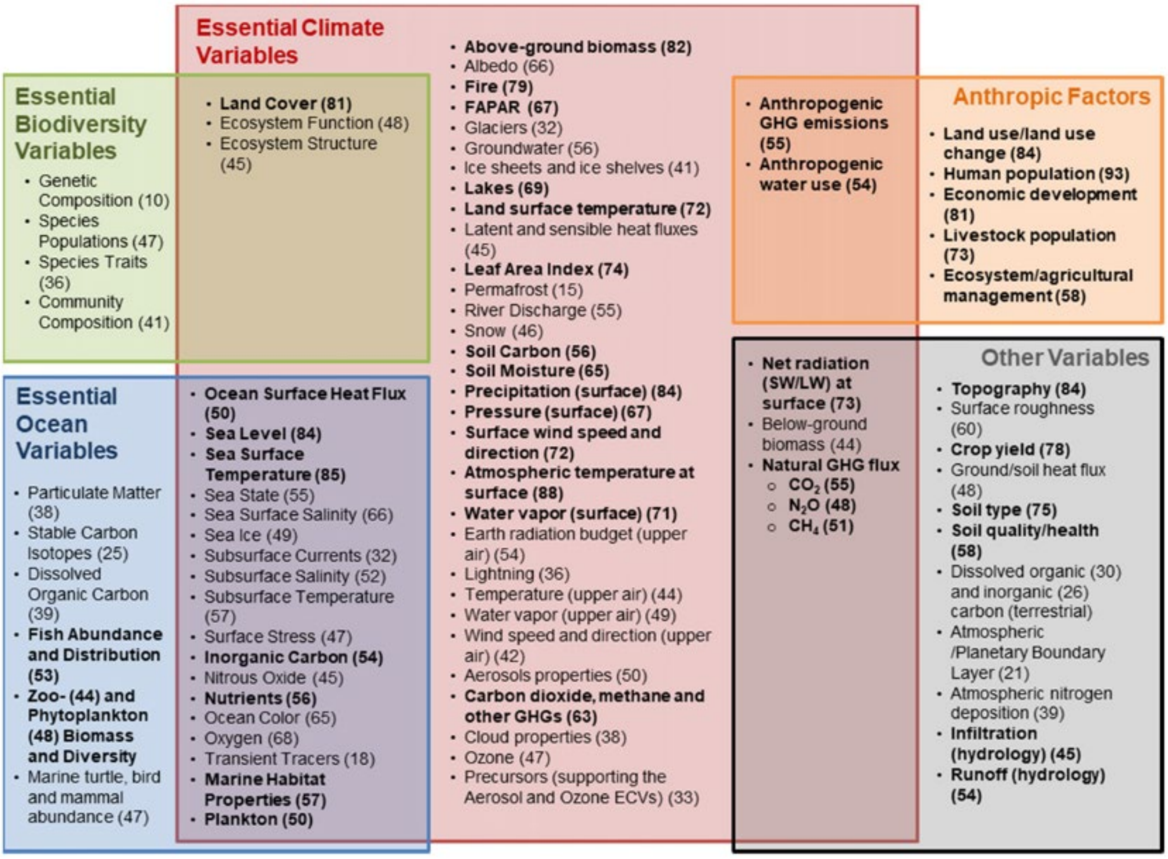

Figure 2 Essential variables for climate services in Africa as identified in the SEACRIFOG project (Lopez-Ballesteros et al. 2018)

In the conceptualization of the Research Infrastructure needs to support Climate services in the KADI project a decision was made in the development of the project not to focus on the routine meteorological observations which have been the focus of multiple other projects and are being addressed through organizations such as the WMO and national meteorological and hydrological organizations. This accounts for the following identified essential variables:

- Land surface temperature
- Snow
- Precipitation
- Pressure
- Surface wind speed and direction
- Atmospheric temperature the surface
- Water vapour
- Earth radiation budget
- Lightning
- Temperature upper Air
- Water vapour upper Air

- Wind speed and direction upper air
- Cloud properties

For the KADI project, the focus has been on the development of 5 major RIs to support Climate services needs and these cover most of the remaining Essential Variables. These include:

1. **A research infrastructure that observes the exchange of carbon between the land surface and the atmosphere.** This RI will provide information relating to
    a. Natural GHG flux for CO_2, water and in certain cases methane
    b. Latent and sensible heat
    c. Net radiation SW/ LW
    d. Below ground biomass
    e. Ecosystem function
    f. Albedo
    g. Soil carbon
    h. Soil moisture
2. **A research infrastructure to support Atmospheric Composition observations,** This RI will provide information relating to:
    a. Carbon dioxide, methane and other GHG concentrations in the atmosphere
    b. Aerosol properties
    c. Ozone
    d. Precursors of ozone and aerosols
3. **A Research Infrastructure to support Biodiversity Observations**, to provide information relating to:
    a. Land cover
    b. Ecosystem structure
    c. Above ground biomass
    d. Leaf area and other plant traits for validation of RS products and model parameterisation
4. **A Research Infrastructure to support Earth System Modelling**
    a. All the above parameters and model outputs
    b. Fire
    c. Glaciers
    d. Groundwater
    e. Lakes
    f. Permafrost cover
    g. River discharge
5. **A research Infrastructure to support Coastal Biogeochemistry Observations**
    a. Ocean surface heat flux
    b. sea level
    c. Sea surface temperature

d. Sea state
e. Sea surface salinity
f. Sea ice
g. Subsurface currents
h. Subsurface temperature
i. Subsurface salinity
j. Surface stress
k. Inorganic carbon
l. Nitrous oxide
m. Nutrients
n. Ocean colour
o. Oxygen
p. Transient tracers
q. Marine habitat properties
r. Plankton

3 Terrestrial Carbon exchange observation research infrastructure

This section refers to the development of a continental RI that focuses on the observation of the exchange of carbon between the land surface and the atmosphere, typically based around the use of eddy covariance (EC) methodologies. This RI includes stations comprised of eddy covariance towers, soil chambers, and meteorological instruments and provide information about the carbon cycle, primarily focusing on carbon dioxide (CO_2), but also methane (CH_4) at the site. Importantly, they are instrumental in the development of Earth System Models, and the validation of remote sensing products. Many of these observations leverage computational techniques, including machine learning (ML)and artificial intelligence (AI), allowing for a broader range of outputs.

3.1 Foundational Characteristics

3.1.1 Theory of Change

An optimised network of carbon exchange observation sites in Africa will provide systematic data for a better understanding of carbon, water and energy fluxes in different biomes and how they change over time and as a response to drivers related to climate conditions and changing land use. Therefore, an adequate network of carbon exchange observation sites would close this gap by providing the necessary quantitative knowledge of the contribution of African ecosystems to the global carbon cycle, especially under the reality of climatic and anthropogenic impacts. Additionally, this data will provide the necessary inputs for satellite remote sensing and Earth System Model verification, and the Africa specific parameterisation of global and regional models.

This type of RI is critical for addressing climate change by providing data and a range of data visualisations to guide users, policies and strategies on carbon management, mitigation, and adaptation. It plays a significant role in understanding how terrestrial ecosystems respond to natural and anthropogenic changes, identifying high risk areas, as well as areas for protection or conservation.

3.1.2 Products, solutions and outputs

The proposed RI should produce its outputs in different forms. This includes the open access publication of the processed data to appropriate national or international databases that will allow researchers to find and utilize the data. An appropriate example would be the international FLUXNET data releases or linkages with the internationally relevant data platforms linked to RIs such as NEON, ICOS or TERN and others. The data from the observation networks should enable researchers to advance the knowledge base relating to the direct observation at the site but also through the application of this information to RS product validation and algorithm development, and communicate those findings through research papers, conference presentations, and workshops etc. There should be scientific publications by researchers using the data from the RI. The outputs of the RI should also enable the international scientific community, national governments, and the private sector to make informed decisions with regards to GHG emissions from Africa. Those decisions can be communicated through instruments such as policies, and legislation and will form part of the international climate negotiations. Moreover, the outputs should also be communicated in the form of booklets, newsletters, and other relevant media to all the interested stakeholders. Individual products that might be appropriate include:

Time series output of the observation parameters presented in an open source and public manner:

Raw Data Products (Eddy Covariance measurements)

- Ambient CO_2 concentrations (ppm)
- CO_2 density (umol mol^{-1})
- 3D wind velocities (m s^{-1})
- Pressure (Pa)
- Temperature (°C)

Ecosystem Flux Data (processed)

- Net Ecosystem Exchange (NEE)
- Gross Primary Productivity(GPP)
- Ecosystem Respiration (Autotrophic Respiration and Heterotrophic Respiration)

Spatial and Temporal Aggregates

- Daily, monthly and annual fluxes of water, carbon and methane
- Regional patterns aggregated across ecosystems or biomes to identify spatial trends in the exchange of water, carbon and methane

Ecosystem Carbon Budgets

- Annual carbon budgets (Total carbon uptake and release at the ecosystem scale)
- Carbon Use Efficiency (Ratio of GPP to total ecosystem carbon release)
- Net Biome Productivity (Carbon balance of a biome considering disturbance such as fires, deforestation)
- Carbon fluxes: Net ecosystem productivity (NPP) and Gross Primary Productivity (GPP), fluxes from land use change

Ecosystem Scale Processes/Parameters

- Canopy conductance and transpiration
- Energy fluxes; latent, sensible and ground heat flux
- Range of biometeorological variables such as solar radiation balance, meteorology, rainfall, wind, atmospheric pressure, soil moisture and temperature
- Methane concentrations and localised emissions tracking

Efforts should be made to convert these outputs to non-expert formats. Further information relating to this will be delivered in Deliverable 3.5 of this project. The creation of visualizations for diverse audiences will facilitate information dissemination and general climate literacy, for example:

- Greenhouse gas inventories for regional and national reporting
- Carbon footprint analysis to assess land use impacts and mitigation strategies
- Risk assessment maps identifying areas at risk of becoming carbon sources, for example Global Forest Watch: https://www.globalforestwatch.org
- Land management decision tools for sustainable forestry and agriculture based on carbon flux dynamics, for example COMET-Planner: http://comet-planner.com
- Renewable energy planning, for example, Global Solar Atlas, https://globalsolaratlas.info, and Wind Atlas for South Africa (WASA): http://wasaproject.info/
- Conservation planning which links carbon storage with biodiversity: The Nature Conservancy Resilient Land Mapping Tool: https://www.maps.tnc.org/resilientland/#/explore
- Validation of RS product outputs, e.g., (Floyd Vukosi Khosa et al. 2020; Maluleke et al. 2024)
- Earth system model validation, e.g., (Floyd V. Khosa et al. 2019)
- Integration with emerging technologies: Artificial intelligence (AI)/machine learning (ML) (AI/ML) applications for flux data, including processing, gap-filling, and prediction. Microsoft AI for Earth: https://www.microsoft.com/en-us/ai/ai-for-earth

3.1.3 Impact pathways

For the proposed carbon exchange observation RI to achieve its intended impacts the following should be considered in this order:

3.1.3.1 Co-design

The co-design of the infrastructure is an important consideration to appropriately position the infrastructure components and ensure that the infrastructure meets the needs of the community. The scientific engagement around open science has tended to focus on the creation of new technological platforms and tools to facilitate sharing and reuse of a wide range of research outputs. This comes with the implicit assumption that once these new tools are in place, researchers and members of the public will be able to participate in the creation of scientific knowledge in more accessible and efficient ways. While many of these new tools have assisted in the ease of collaboration through online spaces and mechanisms, the narrowness of how infrastructure is imagined by scientists who are attempting to apply open science principals tends to put the use of technology ahead of the issues that people are actually trying to solve and fails to acknowledge the systemic constraints that exist within and between some communities (Okune et al. 2018). To ensure there is a co-design aspect in the development the RI to support Carbon exchange measurements, all the relevant or interested stakeholders should come together to plan or design the infrastructure at the appropriate scales, from continental to local. It is likely that the infrastructures will be developed from the local level up considering the funding and organisational constraints, and therefore it becomes essential that these local practitioners engage at national, regional and continental scales to developed appropriate communities of practice.

This entails designing and assessing the feasibility of the network layout in terms of where the stations are likely to be deployed as well as what are the key variables to be measured and why. In addition, RI may require consideration in terms of who is going to finance the RI, i.e. is it going to be all the interested organizations putting together the money or one organisation, and importantly, what are the benefits and challenges for both options. Issues relating to technical maintenance and who is going to be responsible for such, and how all the involved parties are going to benefit at the end will also require careful deliberations.
Co-design and multi-stakeholder engagement optimises the inclusion of crucial components, promotes trust and transparency, and ensures the accessibility and sustainability of the RI (Okune et al. 2018; Flanagan, Haak, and Paglione 2021).

3.1.3.2 Ground-based measurements.

The African carbon exchange RI should focus primarily on the exchange of CO_2 and water vapour between the land surface and the atmosphere, with a special focus on methane in wetlands and aquatic systems, where emissions are expected to be significant. This is vital in understanding the fluxes and the rates of exchange of carbon between the land surface and the atmosphere, the network should be designed to be as inter-comparable as possible, using equipment that is of high quality and meets a prescribed minimum standard. While the approach of standardising instrumentation types and models would optimise the inter-comparability and harmonisation it is understood that this may not be possible in the scope of the governance structures of the network for the supplier regime between the regions or partners.
While there may be scope for variability between instrumentation types, the calibration and reference materials should be traceable to the SI, and there are a number of suppliers of calibration gases and other reference materials that can be utilised. (Please refer to Section 3.2.3)

The African carbon exchange observation RI should form a component three focal observation networks themes stated by (Wohner et al. 2021). These three observation network themes include atmospheric networks to measure the concentrations of CO_2, CH_4, N_2O (and other GHGs in the atmosphere) (Section 4), terrestrial flux tower networks to measure the exchange of CO_2, water vapor and energy fluxes in terrestrial ecosystems (this section), and lastly the ocean observation networks to measure ocean-related GHG fluxes (Section 7). This implies that there needs to be clear and intentional engagement with other RIs or components of the RI to ensure that synergy in these measurements is developed.

3.1.3.3 Data flow and analysis

The flow of data from the flux instrumentation follows the path of:

1. Data Acquisition
    - Sensors collect real-time data.
    - Data is transmitted to a data logger.
2. Raw Data Storage

    - High-frequency raw data is stored on the data logger.
3. Pre-Processing & Archiving
    - If required, data undergoes pre-processing on the logger.
    - Both raw and Level 1 processed data are archived.
    - Automated screening for errors and quality flags to generate Level 2 dataset.
    - Standardized screening methods are applied if available.
4. Final Processing & Standardization
    - Processed through a standardized system.
    - Site-appropriate gap filling and flux partitioning methods applied.
    - Data labelled as a final data product.
5. Data Storage & Analysis
    - All data levels stored in a reliable relational database.
    - Analysis conducted using appropriate tools.

The harmonisation of site-level data in the form of column arrangements and naming conventions should be prioritised to ensure consistency across sites, for example, the Ameriflux base variables (https://ameriflux.lbl.gov/data/aboutdata/data-variables), and the Biological, Ancillary, Disturbance, and Metadata (BADM) system of standards (see (Lopez-Ballesteros et al. 2018) http://www.icos-etc.eu/icos/documents/templates and https://fluxnet.org/badm-data-product/). A standardised list of parameter names for the observations associated with carbon exchange observations is available in Appendix 1 (Standardised naming convention).

3.1.3.4 Validation

By integrating carbon exchange data with remote sensing and modelling products, researchers can better assess the accuracy of variables like GPP or NPP, ET, Land Surface Temperature (LST) and soil moisture from fine and medium-resolution satellite-derived estimates (Landsat, MODIS, Sentinel-2, ECOSTRESS etc.) and advance our understanding of ecosystem processes at multiple scales. EC measurements represent a variable footprint, typically ranging from 100 m to 1 km, depending on factors like tower height, wind speed, and surface roughness. By matching the spatial footprint size with satellite pixel size, aligning the temporal scales, and further filtering the data (for example removing unfavourable atmospheric conditions), a statistical comparison to evaluate the agreement with the datasets can be undertaken. For example, NEE or ET measured through a network of flux towers can be used to validate MODIS estimates of GPP/NPP or ET to help constrain the MODIS signal to achieve greater confidence in the measurement. This will allow room for improvement of the observation network, by defining monitoring needs and locations and will be used in the validation of the model and remote sensing products.

3.1.3.5 Dissemination of information

Data should be openly and freely accessible in the data portal of the managing organization. Information should be disseminated in all applicable ways (i.e., research papers, conferences, workshops, newsletters, booklets, policy briefs and white papers etc.). In the South African context, the SAEON-operated flux systems are already sharing level 1 data on an easily accessible website and are freely downloadable (developed as part of WP3.2 of the KADI project). The international examples of ICOS, TERN, NEON and FLUXNET have demonstrated the value of open date in this context. Data can also be disseminated through global networks, such as Fluxnet, which has historically provided data through periodic releases, (FLUXNET2015) and the up-coming FLUXNET2025. Effort should be made to integrate with other platforms, such as earth observation (for the validation of satellite-derived remotely sensed data) and modelling platforms, for example the CASA (Carnegie-Ames-Stanford Approach) Model (Huang et al. 2022, 2) and the LPJ(Lund-Postdam-Jena) Model (Kallingal et al. 2024). Use of the data to parameterise and validate African-specific models, such as the ESM developed in Pilot 2.1 (Deliverable 2.1). should also be encouraged.

3.1.3.6 Training on usage of data

If the RI is managed by a consortium from different organizations, each organization should make it their responsibility to train the data users about the data. This would be relevant throughout the data processing cycle, from data collection, pre-processing of raw data, and post-processing including gap-filling and flux partitioning. Inadequate knowledge on how to use the data may result in the misuse and misinterpretation of the data. There should therefore, be a standard data use course across all the RI organizations, that will be conducted regularly. Depending on the mode of the operation of the, training dissemination may be centralised in the organisation or as a community of practice that develops between all participating organisations in the network. Drawing on the experience from existing infrastructures such as ICOS, SAEON, Fluxnet, Ameriflux, et cetera could streamline the training process. Within the African community there is a dearth of training within tertiary academic institutions and only a limited number of universities or research groups offer training in this data (See WP3.3). The inclusion of eddy covariance methodology and flux data in courses covering the hydrological and carbon cycle, ecological modelling, or land-atmosphere interactions, etc. would greatly increase the basic understanding of potential data users. Emphasis will need to be placed on developing the technical capacity to ensure that there is a cohort of trained technicians and data managers who are able to maintain and support the long-term operations of this infrastructure. Through the network regular training opportunities need to be implemented with the purpose of 1) training new technicians and increasing the available technical capacity and 2) ensuring that there is a significant amount of harmonisation between operations across the continent. These training activities should focus on hands-on field training including setting up and maintaining EC towers, calibrating sensors, collecting data and metadata.

3.1.3.7 Equip stakeholders with knowledge

All the knowledge obtained from the RI should be equally available and accessible to stakeholders, this includes a dedicated focus on making the data freely available under FAIR principles and where appropriate providing necessary metadata and instrumentation management records. Beyond the general data management, attempts for the transfer of knowledge to stakeholders should be made, including aspects of scientific understanding gained, local and international evidence and interpretation and a feed into the policy and management strategies.

The knowledge should address the needs and requirements from all actors/stakeholders, enabling them to use it to their benefit. In this context it will require the development of data products and the scientific support from the RI to support the community or actors/stakeholders in utilising the information and the knowledge that has developed through it. This will require the availability and accessibility of data platforms (that store the data in user-friendly formats.

3.1.3.8 Actions taken based on the knowledge from the Carbon Exchange RI

As the RI intends to support and inform policy developments and implementation at multiple geographical scales, it needs to provide the relevant data and research outputs identified by the actors/stakeholders. This information should be in accessible and understandable format – i.e. translating high-level scientific outputs into policy briefs. The RI should further support the actionable implementation through providing continued monitoring. For instance, areas with high carbon storage value could be targeted for legislation or alternative land use options that slow land transformation. To measure the success of such actions, continued monitoring by the RI could inform on flux trends from changed land use practices, thereby providing the opportunity to adapt actions if necessary

3.1.4 Monitoring, Evaluation and Learning of Impacts

The impact of the RI should be regularly monitored. This involves bringing together the stakeholders to revise what was said to be the goal of the RI. The actors should use a set of indicators to evaluate the goal or objective of the RI. Participatory Monitoring Evaluation Reflection learning (PMERL) is a tool that is often used to monitor the activities in such infrastructures (Holte-McKenzie, Forde, and Theobald 2006; van Rees et al. 2022). This tool can be adopted to monitor the impact of a RI. The tool is self-explanatory, meaning after the actors/stakeholders have participated in the development of the RI they should be actively involved in all the following steps which are monitoring, evaluation, reflection and learning. PMERL gives an opportunity to improve the performance of the RI.

3.1.4.1 Co-concepts

In every step of establishing the RI, co-design, co-creation, and co-production is fundamental. All the relevant or interested actors/stakeholders should be involved in every step; from planning of the RI to finally disseminating the product or output. There should be clear understanding who is involved in which stage if not all. It should be considered that some actors/stakeholders will join at the later stages.

3.2 Observations, data sources and technologies

3.2.1 Observations, measurements and monitoring

3.2.1.1 Availability of measurements in Africa

Recent studies (Maluleke et al. 2024; Ciais et al. 2011; Merbold et al. 2021; Ernst et al. 2024) have noted that the network of eddy covariance sites on the African continent is sparse, thus the contribution of African ecosystems to the global carbon cycle has been insufficiently studied. It is further argued that there are large uncertainties that exist in GHG emissions from Africa, making the development of appropriate mitigation plans a challenge (Ernst et al. 2024).

A total of 51 sites have been identified across the continent, including both operational and non-operational eddy covariance sites Figure 4 and

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APPENDIX 2. At present an estimated 23 sites currently being operational.

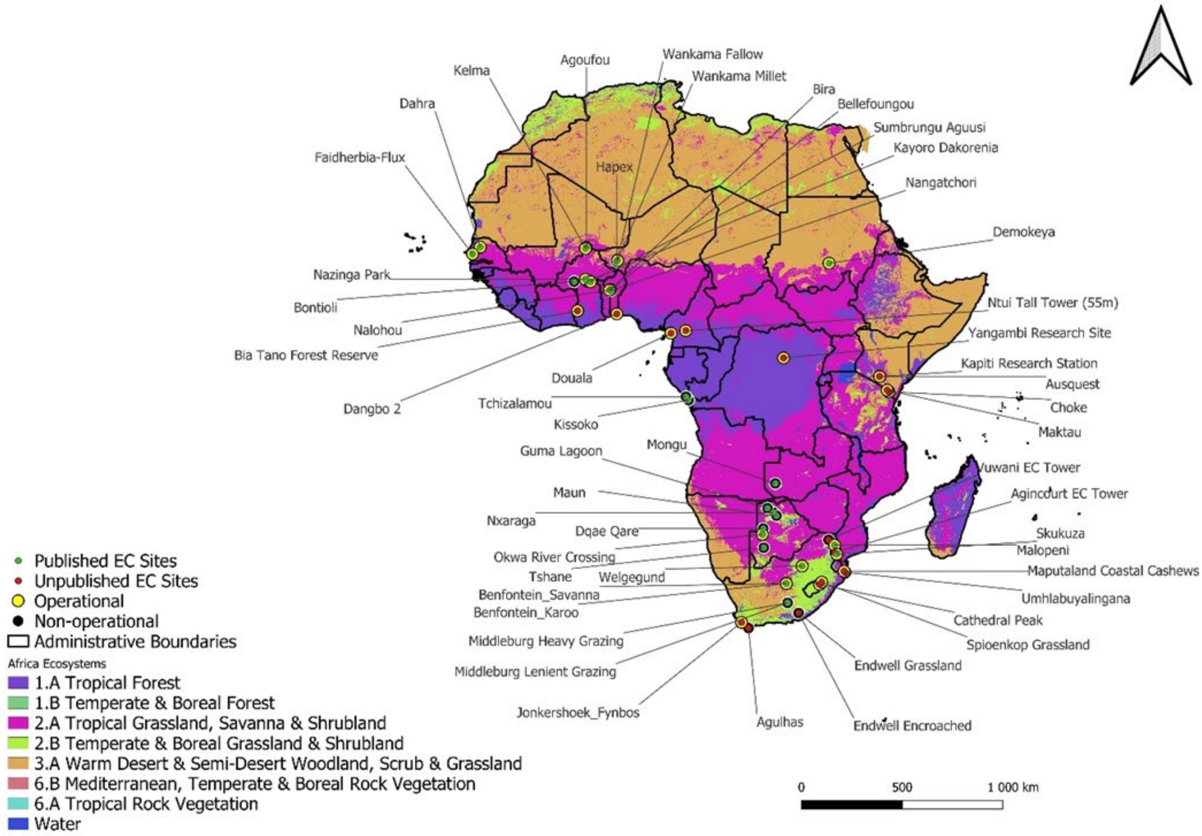

Figure 3 Historic and operational flux measurements sites in Africa under major vegetation types, Map after (Sayre et al. 2013)

These 51 sites represent 5 of 7 macro vegetation classes on the continent (as defined by Sayre et al 2013 as an indicative vegetation classification system), with 53% of the sites being in the class: Tropical Grassland, Savanna & Shrubland according to the land classification system used by used by (Sayre et al. 2013), this class makes up 35% of the total continental land cover.

Table 1 Land area of vegetation classes (after (Sayre et al. 2013)) with number of eddy covariance sites identified in each

Vegetation Class	Land area (km2)	Percentage (%)	EC Sites	Percentage (%)
1.A Tropical Forest	4638241	15,53	8	15,69
1.B Temperate & Boreal Forest	143008	0,48	1	1,96
2.A Tropical Grassland, Savanna & Shrubland	10557072	35,35	27	52,94
2.B Temperate & Boreal Grassland & Shrubland	1863844	6,24	7	13,73
3.A Warm Desert & Semi-Desert Woodland, Scrub & Grassland	12416669	41,57	8	15,69
6.A Tropical Rock Vegetation	3866	0,01	0	0,00

6.B Mediterranean, Temperate & Boreal Rock Vegetation	12409	0,04	0	0,00
Water	230667	0,77	0	0,00
Total	29865776		51	

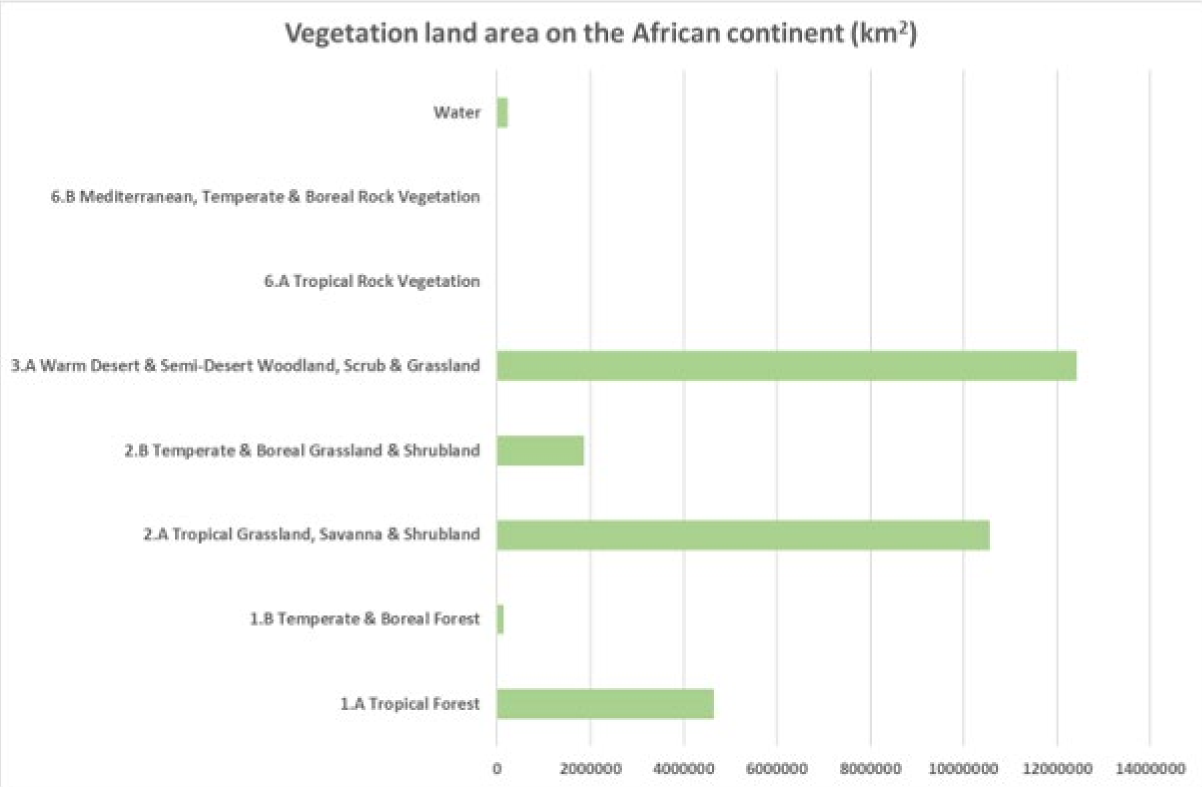

Figure 4 Vegetation Class per land and land area after (Sayre et al. 2013)

Table 2 Major Vegetation groupings with vegetation subclasses represented by eddy covariance sites on the African Continent ((Sayre et al. 2013)

Vegetation Groups	Vege Subclasses	Eddy Covariance Sites
Tropical Forests (1.A)	Tropical Lowland Humid Forest (1.A.2)	7
	Tropical Seasonally Dry Forest (1.A.1)	1
	Tropical Montane Humid Forest (1.A.3)	0
	Tropical Flooded & Swamp Forest (1.A.4)	0
	Mangrove (1.A.5)	0
Temperate Forests (1.B)	Temperate Flooded & Swamp Forest (1.B.3)	1
	Warm Temperate Forest (1.B.1)	0

Grasslands, Savannas, and Shrublands (2.A & 2.B)	Tropical Lowland Grassland, Savanna & Shrubland (2.A.1)	25
	Tropical Montane Grassland & Shrubland (2.A.2)	0
	Tropical Freshwater Marsh, Wet Meadow & Shrubland (2.A.5)	2
	Temperate & Boreal Freshwater Marsh, Wet Meadow & Shrubland (2.B.6)	0
	Temperate Grassland, Meadow & Shrubland (2.B.2)	3
	Mediterranean Scrub & Grassland (2.B.1)	1
	Salt Marsh (2.B.7)	2
	Temperate & Boreal Grassland & Shrubland (2.B.3)	1
Desert & Scrubland (3.A)	Warm Desert & Semi-Desert Scrub & Grassland (3.A.2)	8
		0
Rock Vegetation (6.A & 6.B)	Tropical Cliff, Scree & Other Rock Vegetation (6.A.1)	0
	Temperate & Boreal Cliff, Scree & Other Rock Vegetation (6.B.2)	0
		51

A full list of the known flux sites is presented in APPENDIX 2

A Carbon Exchange RI will need to utilise the most appropriate instrumentation to accurately measure the exchange of Carbon between the land surface and the atmosphere; this will primarily be based on the use of the eddy covariance techniques.

The eddy covariance system has been developed to quantify the exchange of CO_2, water vapour and energy between the land surface and the atmosphere (Burba 2013; Kato et al. 2013; Bombelli et al. 2009; Rebmann et al. 2018 and others). The system consists of a gas analyser that records high frequency measurements of the atmospheric concentrations of water vapour and CO_2 (other instruments measuring CH_4 are available), and a high frequency 3D sonic anemometer for measuring wind in both the vertical and horizontal dimensions and the sensible heat. In addition, the towers typically host a suite of additional biometeorology measurements to understand the flux measurements being taken. These include meteorological measurements (wind speed, wind direction, temperature, pressure, humidity and precipitation), radiation balance measurements (incoming and outgoing short and long wave radiation and soil heat flux), soil conditions (moisture and temperature at various depths). In the South African context eddy covariance systems have been procured by SAEON/EFTEON and consist of the instruments and variables as presented in Table 3, similar instrumentation would be used in other local and international networks. Across the established networks, different approaches have been taken in the levels of standardisation of the instruments used, it is recommended that at a minimum a similar set minimum instrument specification are used across all networks and sites to be established across the continent and to emphasise comparability with other international networks.

The location of the observation sites should ideally represent all the major types of biomes in Africa (Figure 4) to reflect the diversity of possible carbon flux processes on the continent. The spatial information will determine the size and arrangement of the instruments (e.g. flux tower). The vegetation information will help to determine the height and desired footprint of the equipment. The system that measures ecosystem-level fluxes should always be mounted at the height above of the vegetation canopy. Additionally, discrepancy between modelled and measured concentrations that would be expected at a particular site should be taken into consideration. The review or auditing of existing RI should first be done to obtain the spatial distribution of the existing networks. New stations should then be deployed where there are gaps.

The exact location of the proposed RI should be determined by the practical considerations such as topography and the presence of existing infrastructure. Measurements that should be taken in different RI themes should possibly include all the essential variables identified (Lopez-Ballesteros et al. 2018; Bombelli et al. 2009). To avoid gaps in data, the stations should be regularly maintained to produce quality data. Long-term quality data enable the detection of trends. Examples of existing standard operating procedures are published, and it may be a valuable activity of a continental community of practice to adopt harmonised methods and procedures.

3.2.2 Design requirements of the Carbon exchange RI

The biogeochemistry platform aims to provide long-term process information relating to the cycling and storage (pools and fluxes) of carbon, nitrogen, phosphorus, sulphur, and other biogeochemical cycles between the soil vegetation atmosphere hydrosphere continuum. The biogeochemistry platform consists of a number of measurement systems such as eddy covariance, atmospheric deposition, water chemistry; some of these are important for other thematic areas, with significant interlinkages. Repeated measurements of the aboveground biomass, a stock change approach, are an important addition to carbon monitoring. These provide linkages to biodiversity, process-based models, and earth observation datasets.

3.2.2.1 In situ instrumentation in a Carbon exchange RI

Table 3 Instrumentation and Variables measured on the Eddy Covariance towers, these include

Instrument	Variable	Shared with other Research Infrastructures considered under this study
Essential Variables for Carbon and Water Exchange using the Eddy Covariance method		

Instrument	Variable	Shared with other Research Infrastructures considered under this study
CO_2/H_2O gas analyser and Sonic anemometer - either as separate systems or integrated	CO_2 Concentration, from which flux is derived	Atmospheric Composition
	H_2O Concentration, from which flux is derived	Atmospheric Composition
	Sonic temperature, from which flux is derived	Meteorology
	Wind u direction	Meteorology
	Wind v direction	Meteorology
	Wind z direction	Meteorology
Barometer	Air pressure	Meteorology,
Associated Biometeorological parameters for context and interpretation		
Fine wire thermocouple	Air temperature	Meteorology
Temperature and humidity sensor	Atmospheric temperature	Meteorology
	Humidity	Meteorology
Heat flux plate	Soil heat flux	Meteorology,
PAR Sensor	Photosynthetically active radiation	Meteorology, Biodiversity
Net Radiometer	Incoming shortwave radiation	Meteorology
	Outgoing shortwave radiation	Meteorology
	Incoming longwave radiation	Meteorology
	Outgoing longwave radiation	Meteorology
Rain gauge	Precipitation	Meteorology,
Soil moisture sensors	Soil moisture content	Meteorology,
Soil temperature sensor	Soil temperature	Meteorology
Wind sensor	Wind direction	Meteorology
	Wind speed	Meteorology
Ancillary/supporting measurements		
CO_2/H_2O and CH_4 analyser	CO_2 concentration (ppm), CO_2 flux (μmol m^{-2} s^{-1})	Atmospheric Composition

Instrument	Variable	Shared with other Research Infrastructures considered under this study
• FTIR multi-gas analyser • IR gas analyser	CH4 concentration (ppm) CH4 flux (µmol m⁻² s⁻¹)	Atmospheric Composition
	H_2O concentration (mmol mol⁻¹) H_2O flux (mmol m⁻² s⁻¹)	Atmospheric Composition
	Soil temperature	Land surface and biodiversity / and meteorology
	Soil moisture	Land surface and biodiversity / and meteorology Atmospheric Composition
Time-lapse camera (or repeated fixed-point photography)	Phenology	Biodiversity
Spectrometer (hyper/multi spectral sensor)	GVI/Phenology/NDVI/Sun-induced fluorescence	Biodiversity
• Handheld ceptometer • Handheld canopy analyser • Fisheye lens digital camera (digital hemispherical photography)	Leaf Area Index	Biodiversity, Earth System models
LiDAR sensor	Canopy height, AGB estimation	Biodiversity

3.2.2.2 Location and mounting infrastructure

The eddy covariance towers will need to be designed for long-term deployment, with a design focus on longevity and continuity of operations, safety of staff accessing the towers and protection against lightning and other forms of damage, including vandalism.

The height of the instrumentation above the surface layer is an important characteristic of the site and should be chosen to appropriately position the instrumentation in the context of the surface in which they are operating, as the deployment height impacts the area that the instrument observes. This positioning is therefore very context specific as the site researchers should aim to position the instruments to observe the vegetation of interest.

Instrumentation must be located at a distance of 2 times the width of the tower from the tower structure (WMO and NEON requirement) to minimise the impact of the turbulence created by the Tower structure. All towers should have an independent wind sensor at a height of 10 m to have a standardised WMO equivalent wind measurement

3.2.2.3 Mounting infrastructure

Each tower structure should meet the following requirements:

- Lattice mast
- Manufactured to withstand wind speed of at least 1/50-year gust as per the local wind design code
- Climbable structure with safe working load, to meet appropriate national and international equipment standards
- Durable (for long-term 15-year deployment), it should be made of or coated with a non-corrodible material, locations may be subject to sea salt influence should be given particular attention to ensure corrosion resistance
- Load Capacity: Supports up to 200 kg of instruments, with safety factors accounted for (load-bearing capacity of around 500-600 kg), this should also include the mass of the researchers accessing the instrumentation
- Fatigue Resistance: Materials should be selected and designed to withstand long-term fatigue and deformation over the lifespan of the tower (typically 10-20 years).
- Lightning protection meeting appropriate local standards, this is vital to protect equipment that is mounted on the tower.

3.2.2.4 Power supply

Power supply is a critical component of an eddy covariance system, especially when it is deployed in remote areas where access to electricity may be limited. The system requires a reliable, continuous power source to operate the sensors, data loggers, communication equipment, and any associated equipment for monitoring, data storage, and transmission. Below are the power supply requirements and options for an eddy covariance system deployed in a remote area:

The power requirements of an eddy covariance flux tower depend on several factors, including the number of instruments, data acquisition systems, and auxiliary equipment (such as heating or cooling for sensors). Below are typical power demands:

3.2.2.5 Key Components and Their Power Consumption

- Sonic Anemometer (3D Wind Velocity Sensor):
  - Power consumption: Typically, 1-3 W (depending on the model).
- Gas Analysers (e.g., IRGA for CO_2 and H_2O):
  - Power consumption: Can range from 5-10 W per instrument, depending on the type of analyser.
- Radiation Sensors (Pyranometers, Pyrgeometers, Net Radiometer):
  - Power consumption: Ranging around 5-10 W per sensor.
- Data Logger/Controller:
  - Power consumption: Typically, 5-15 W (depending on the model and sampling frequency).
- Heaters (if necessary for temperature-sensitive sensors):

    - Power consumption: 10-50 W per sensor, depending on the ambient temperature and equipment requirements.
- Communication Equipment (e.g., satellite, radio, or cellular modems for data transmission):
    - Power consumption: 10-30 W depending on the communication technology and data transmission frequency.

3.2.2.6 Total Power Consumption

The total power consumption for a typical eddy covariance system is often in the range of 30-100 W for standard systems. For more sophisticated setups with additional sensors or higher sampling frequencies, the power demand could go higher.

- Typical Power Requirement Range: 50-150 W (depending on the number of sensors and communication needs).
- Peak Power Consumption: Short-term spikes may occur during data acquisition or transmission, but power supply systems must handle these peaks.

In remote areas, where there is no access to the electrical grid, power must be generated locally. The following are the most common power supply solutions:

3.2.2.7 Solar Power

Solar power is the most common and sustainable option for providing energy to remote flux tower installations. The system typically consists of solar panels, a charge controller, batteries for energy storage, and associated wiring.

Solar Panels:

- Size: The number and size of solar panels depend on the power requirements of the system. For a typical system with a power consumption of 50-150 W, solar panels rated at 100-300 W (peak power) are commonly used. Choice of the solar panels depends on considerations such as the location and weather conditions (e.g., sunlight hours, seasonal variations)

- Charge controller, this protects the battery from overcharging and ensures that the correct voltage is supplied to the system.

- Batteries, batteries are required to store energy for night-time operation or cloudy days. Deep-cycle lead-acid or lithium-ion batteries are often used. Battery capacity is typically designed to supply power for at least 2-3 days without sunlight (in case of bad weather or low solar radiation). For example, a system requiring 100 W, a 12V 100Ah battery could be used (which would provide 100 W for about 12 hours, factoring in system efficiency and safety margin). The total energy generated by the solar panels should exceed the system's daily consumption to allow for storage in the batteries.

- The power supply components are often a prime target for vandalism or theft and consideration needs to be made to ensure that the components are protected.

3.2.3 Calibration and Maintenance Routines

3.2.3.1 Calibration

Calibration is essential for ensuring that the measurements of key variables (e.g., wind velocity, gas concentration, temperature, radiation) are accurate and reliable. For eddy covariance systems, calibration should be done regularly and after any significant equipment changes, such as sensor replacement or ecosystem disturbances such as fire.

- Calibration of the Sonic Anemometer
  - Frequency of calibration: Annually or after maintenance, sensor replacement, or significant changes in measurement conditions.
- Calibration of the Gas Analyser
  - Frequency of calibration: Monthly or as per the manufacturer's recommendation, more often if environmental conditions cause large fluctuations in sensor readings.
- Calibration of the Radiation sensors (pyranometers, pyrgeometer, net radiometer)
  - Frequency of calibration: Annually, or according to the manufacturer's instructions, or after extreme environmental events.
- Calibration of the Temperature and Humidity Sensor
  - Frequency of calibration: Annually or as required by the specific sensor used.
- Calibration of the Data Logger and System calibration
- Frequency of calibration: Annually or after major system upgrades

3.2.4 Routine Maintenance

Routine maintenance is necessary to keep eddy covariance systems operational and to ensure that data are being captured and transmitted correctly. This can involve cleaning, replacing parts, or checking system integrity. Different types of instrumentation may require different maintenance schedules thus should be considered when selecting instrumentation.

3.2.4.1 Cleaning Sensors

- Frequency: Monthly or more frequently if the site is dusty or has high humidity.
- Procedure:
  - Sonic Anemometer: Clean the sensor’s surface with a soft brush or compressed air to remove dust, dirt, or moisture that might obstruct the sonic paths or affect airflow.
  - Gas Analysers: Clean or replace filters if applicable. Ensure that the air intake is not blocked by debris (if enclosed path), dust, or spider webs. Gently clean the sensor head with a damp cloth.

  - Radiation Sensors: Clean the dome or lens of pyranometers and pyrgeometers. Use soft microfibre cloths and avoid abrasive materials. Ensure that no dust or snow accumulates on the sensor's surface, as this could affect measurements.
  - Temperature and Humidity Sensors: Use a soft cloth to wipe the sensor housing, and check for any condensation build-up.
- Tools: Soft brushes, compressed air, microfiber cloths, and non-abrasive cleaning solutions.

3.2.4.2 Visual Inspection and Mechanical Check

- Frequency: Monthly or after any major weather event (e.g., storms, hail).
- Procedure:
  - Inspect the tower structure for signs of rust, corrosion, or structural damage. Tighten any loose bolts or fasteners.
  - Check the alignment and levelling of all sensors. Misalignment can lead to measurement errors.
  - Ensure that all mounting brackets are secure and that there is no excessive movement or vibration on cross arms.
  - Inspect cabling and wiring for damage, wear, or exposure to the elements. Ensure cables are protected from UV degradation or rodent or wild animal damage.
- Tools: Wrenches, levellers, and basic hand tools.

3.2.4.3 Battery and Power Supply Check

- Frequency: Monthly or more frequently in extreme weather conditions.
- Procedure:
  - Check the battery voltage to ensure there is adequate power for the system. Low battery levels may indicate a need for solar panel recalibration or battery replacement.
  - Verify the charge controller is working correctly. Ensure that batteries are charging fully during daylight hours.
  - Clean and inspect the solar panels for dirt, bird droppings, or obstructions that could reduce energy capture.
- Tools: Mustimeter, battery tester, and cleaning tools for solar panels.

3.2.4.4 Communication and Data Transmission Check

- Frequency: Monthly or after extreme weather.
- Procedure:
  - Ensure that data transmission (e.g., radio, or cellular network) is functioning correctly.
  - Test that data is being transmitted successfully to the data centre or remote server. Monitor for any loss of signal or transmission failures.
  - Check for any system errors or alarms that indicate communication problems.

- Tools: Communication diagnostic software and network tools.

3.2.4.5 Environmental Protection

- Frequency: As needed (following storms, extreme temperatures).
- Procedure:
    - Ensure that any weatherproofing (e.g., enclosures for electronics, protective coatings) is intact and free from wear or damage.
    - Inspect protective covers on sensors to prevent damage from wildlife.
    - Create firebreaks around an agreed distance from the tower as preventative measure in case of accidental fires
- Tools: Weatherproofing materials, covers, grasscutter, and inspection tools.

3.2.5 Documentation and Record Keeping

- Keep detailed logs of calibration activities, maintenance routines, sensor replacements, and any errors or failures that occur. This helps track the long-term performance of the system and identify any issues early on.
- Record all sensor calibration certificates and details about any changes or adjustments made to the system.

3.2.6 Issues of security to prevent vandalism

Some existing sites have experienced issues relating to equipment vandalism and theft, which have resulted in extended periods of data loss and requiring expensive instrument replacements and fixing. To counteract this, security upgrades have been implemented to safeguard items such as solar panels and battery packs used in remote sites. Exposed instrument cables where it has not been possible to have them under cover however remain susceptible to vandalism cuts. The following steps have been identified to form a foundation for preventing vandalism:

3.2.6.1 Security Measures

- Lockable Enclosures:
    - Use weatherproof, lockable enclosures to house sensitive equipment such as data loggers, power supplies, communication devices, and any controllers. These enclosures should be made of durable, tamper-resistant materials such as steel, aluminium, or reinforced plastic/fibreglass.
    - Install locks or security bolts that are difficult to tamper with. Use tamper-evident seals to detect if someone has attempted to open the enclosure.
    - Consider ventilated enclosures to prevent overheating of electronics but still provide protection against direct physical interference.
- Surveillance Cameras:

    - If possible, install security cameras or motion detectors to monitor the station. The presence of visible surveillance can act as a deterrent against vandalism.
    - Remote monitoring can be set up via webcams or mobile apps, especially in locations with a stable internet connection.
- Fencing or Barriers:
    - Install fencing or other physical barriers around the monitoring site to create a protected zone. This can be a simple chain-link fence or barbed wire, that prevents unauthorized access.
    - Use signage to clearly mark the area as private property or as a restricted zone for research purposes.
- Bury or Conceal Cables:
    - Run cables underground or within protected conduits to prevent easy access or damage from human interference or animals, it has been found that in remote conditions digging and burrowing animals can cause significant and costly damage, encasing the cables in conduit and burying them
    - Ensure that any exposed cables (e.g., for power or data transmission) are shielded or armoured to prevent them from being cut or tampered with.
- Non-obtrusive Design:
    - Ensure that the equipment is not highly visible from a distance. A low-profile design can reduce the likelihood of attracting attention. For example, hide instruments within natural vegetation or camouflage structures to blend into the environment.
- Restricted Access:
    - Limit access to the monitoring station to authorised personnel only. Implement a clear access control policy and provide keys, codes, or access cards only to individuals who are necessary for the operation and maintenance of the station.
    - Maintain detailed access logs for anyone who enters the site. This could include physical sign-in sheets or digital logs that track who has interacted with the system and when.

- Warning Signs:

    - Place clear, visible warning signs on and around the monitoring station indicating that it is an active research site or environmental monitoring station. Signs can include penalties for tampering or vandalism to inform potential vandals of legal consequences.
    - Make it clear that tampering or damaging the equipment may be subject to legal action and fines.
- Engage Local Communities:
    - If the site is located near populated areas, consider reaching out to the local community to raise awareness about the purpose of the monitoring station. Community involvement and a sense of ownership may help foster respect for the equipment and discourage vandalism.
    - Consider partnerships with local authorities, environmental groups, or other stakeholders who can act as vigilant observers or report suspicious activities.

- Insurance Coverage:
    - Consider insuring the equipment against vandalism, theft, or damage, especially if the instruments are expensive or critical to the project.
    - Work with an insurance provider to understand the risks and coverage options for remote environmental monitoring sites.
- Backup Systems:
    - Implement redundant systems (e.g., backup power supplies, secondary data loggers) so that if an instrument is damaged or tampered with, the system can still function with minimal data loss.

3.2.7 Location of Carbon Exchange Observation Infrastructure

While the exact scope of the location's observation infrastructure will be difficult to decide at this point, it will be necessary to ensure that the diversity of vegetation systems or biomes are represented. In Figure 3 the distribution of existing and historic flux measurement sites is presented. The distribution of flux observations against the vegetation coverage is expressed in Table 1 this indicates that the existing observation network represents the spatial coverage of most of the African Ecosystems reasonably well except for the arid sites, although these may be of lesser importance in terms of understanding the carbon cycle. The larger problem is that the number of active sites is vanishingly small (22 active sites across the continent at present) and requires a considerable expansion to adequately represent the diversity of ecosystems, climatic zones, and land uses across the continent. Presently most observation sites are in West Africa and South Africa with a significant gap in the central regions of the continent.

While it is difficult to adequately estimate the appropriate number of carbon exchange observation sites that would be required to represent the natural ecosystems on the continent and their diverse land used an approach that may be appropriate is to utilise a continental ecosystem mapping approach and attempt to close the gaps in ecosystem coverage. Using the Terrestrial Ecosystem Map of Africa (Sayer 2013) a total of 126 Macro ecosystem types are defined

This terrestrial ecosystem map of Africa ideally provides a map overview of the types of vegetation present as they are categorised by major biomes and functional types to enable the assessment of their representativeness on the continent. In addition, being aware of the representativeness of vegetation on the continent would allow a network of EC sites that captures the diversity of fluxes across different ecosystems, as well as being able to identify and prioritise areas with rare of ecologically significant vegetation types to capture unique fluxes that might be underrepresented – ensuring spatial heterogeneity in the site selection process.

Using a vegetation map overview would also enable the overlaying of additional environmental data layers (such as soil type, topography and hydrology) as vegetation is often closely linked to these factors. In addition, including the climate and phenology data would account for the seasonal and climatic variability in the area. Combining these layers with satellite imagery or vegetation indices (such as NDVI or EVI) would help refine the site selection as these indices can provide real-time information on vegetation health and productivity to enable the selection of sites with high temporal or spatial variability in fluxes.

While the aim would be to represent all the 126 Macro ecosystems, a map overview with other relevant layers (elevation, terrain, road networks) would provide accessibility assessments to ensure that selected sites are accessible for installing and maintaining eddy covariance equipment. In other instances, very dense vegetation (thick forests) may present challenges in terms of sensor installation and maintenance, thus for practical considerations, it could be useful to select sites in more open areas or where vegetation density allows for easier installation. By carefully selecting sites based on vegetation maps and their ecological context, this site selections process will enable a robust network of eddy covariance sites that can provide valuable data on carbon fluxes (as well water and energy) across different ecosystems.

3.2.8 Costing of setting up a carbon observation network

Table 4 approximate setup costs for Carbon exchange observatories

Initial Setup Costs	Estimated Costs (€)
EC measurement System:	
Gas analysers (CO_2, H_2O, CH_4)	€50,000 – €75,000
3D Sonic Anemometer	€10,000 – €30,000
Data Acquisition System	€10,000 – €25,000
Biometeorological sensors (temperature, soil moisture, radiation)	€5,000 – €15,000
Estimated once-off cost for measurement equipment	€75,000 – €145,000
Site Setup Costs:	
Tower Installation	€3,500 – €15,000
Power Supply Setup (solar panels, battery systems, backup generators)	€5,000 – €10,000
Telecommunication systems (cellular/radio for data transfer/satellite/Wi-Fi)	€300 – €1,000
Estimated once-off cost for site setup	€8,000 – €26,000
Labour and Expertise:	
Field Technician and Installation team (technicians, research staff, external contractors)	€2,500 – €5,000
Estimated once-off cost for labour	€2,500 – €5,000
1. Operational and Maintenance Costs (Annual)	
Routine Maintenance and Calibration:	

Initial Setup Costs	Estimated Costs (€)
Calibration and Maintenance	
Replacement parts	€1,000 – €3,500
Cleaning and Equipment Inspections	€750 – €1,500
Estimated Annual Maintenance Costs	€1,750 – €5,000
Personnel Costs:	
Technician Salary	€30,000 – €50,000
Estimated Annual Personnel Costs	€30,000 – €50,000
Data Management and Storage:	
Data storage and Backup	€3,000 – €8,000
Computing/Software Licences	€2,000 – €5,000
Estimated Annual Data Costs	€5,000 – €13,000
Transportation & Site Access:	
Field Visits and Travel (depends on site location, remote/hard to reach areas)	€3,000 – €5,000
Estimated Annual Travel Costs	€3,000 – €5,000
Consumables:	
Gas Calibration Standards	€2,000 – €4,000
Miscellaneous Consumables (batteries, replacement parts and other equipment maintenance)	€1,500 – €2,500
Estimated Annual Consumables Costs:	€3,500 – €6,500
Total Cost Range	€128 750 – €255,500

The total annual costs of operating an eddy covariance site, based on the list above, would range in the following categories:

- Low Range (simpler sites, fewer sensors, fewer personnel): €130,000 – €200,000

- Mid-Range (more complex sites with multiple sensors and a small team): €200,000 – €250,000

- High Range (remote sites, extensive monitoring, high-end equipment, large teams): €250,000+

3.3 Digital Data

3.3.1 Primary digital data

This speaks to the data related to the theme which the particular RI operates in the case of carbon exchange observation RI, data should be divided into the flux measurements for carbon water and energy (and potentially methane) and the biometeorological data (weather climate soil conditions). Data could be measured from the flux tower at the frequency of 10 or 20 Hz. The last theme of carbon RI is the ocean, here the data that should be collected is the air-ocean fluxes using any of the following: research vessels, moorings, buoys and commercial vessels (see this theme expanded in the section ‘Research infrastructure for Coastal Biogeochemistry’, below).

3.3.2 Secondary digital data

Secondary data is crucial as it helps the RI to tie its primary data context. Secondary data could be the remote sensing data that could be validated by the in-situ data, for example the NEE from the flux tower measurements to validate MODIS, NEE or PSnNet. In addition to remotely sensed data, maybe secondary data could be in the form of supplementary vegetation assessments such as SEOSAW plots.

3.3.3 Digital infrastructures

Each theme of the carbon exchange observation RI should have a digital infrastructure that is suitable for its data type. This would primarily be used as an organized system designed to store, manage, and facilitate easy access to high-frequency data. This infrastructure must accommodate large volumes of real-time data, complex metadata, and allow for robust processing and querying. The infrastructure should consist of tools to analyse incoming data until it is in a format suitable for sharing.

3.3.3.1 Data Collection & Sensor Integration

Key components of a data processing and storing tool will include its ability to collect data from various sources such as databases and directly from sensors as well as ingest and integrate these data into the system whether in batch or in real-time.

3.3.3.2 Data Pre-processing & Quality Control

Vital to the storage process will be its ability to clean, filter, aggregate and transform raw data into usable formats. Raw data often require initial pre-processing, such as filtering noise, correcting for sensor drift, and removing spurious measurements. In addition, these processes should have embedded mechanisms to ensure the quality, accuracy and consistency of the data inputs. Since there are a series of calculations associated with carbon fluxes, the system should be able to embed functions and algorithms for running calculations, analytics or other necessary processing workflows. For example, this can include flux calculations, corrections for atmospheric conditions for the transformation of raw data into usable flux measurements.

3.3.3.3 Database Architecture

In a Relational Database Management System (RDBMS),

- **Tables and Schema Design:** Key data entities can include sensor data as well as metadata (location, sensor type, site information), timestamps, and calculated fluxes and additional biometeorological variables.

- **Time Series Data:** The core of eddy covariance datasets is often time-series data, which requires an efficient indexing strategy, typically by timestamp and location, to support quick retrieval and analysis over a multisite-multivariable database.

- **Metadata Tables:** These contain detailed information about the deployment site (coordinates, elevation, vegetation type) and sensor specifications (calibration data, measurement height). These are important variables required for the processing of site-specific raw data.

- **Data Partitioning:** Large datasets may benefit from horizontal partitioning based on site location, sensor ID, or date ranges to distribute load and improve performance and usability.

3.3.4 Data Storage

The database should store both raw and processed files and include possibilities of storing other types of data such as sensor data (numerical values), calculated fluxes, and metadata (descriptive text, numerical attributes). Since multiple datasets from different carbon exchange platforms, the system should be able to have indexing mechanisms to allow fast lookup and retrieval of data by using tools that allow users to query and retrieve data efficiently.

As this database will be handling large sizes of high frequency data, there is a need for efficient storage methods such as compressed binary formats or specialized time-series databases may be used for performance and space optimisation. In addition, older data may need to be archived to reduce load on the primary database. The system should support easy retrieval of archived data for analysis when necessary.
While this is an open access platform, access control measures will be put in place for user authentication and authorisation. In addition, audit logs to monitor who accessed and modified data on the platform will allow data security. For further data security measures, the backup and recovery strategies should allow redundancy in the system to replicate data across multiple locations for improved fault tolerance as well the ability to quickly restore operations in case of large-scale failures.

3.3.5 Data Access and Querying

An API (Application Programming Interface) enables external applications or researchers to query and retrieve data. This allows integration with analytical tools and web applications.

Data Query Language: SQL for relational databases or specialised query languages for time-series databases. Queries might include spatial searches (based on site coordinates) and temporal searches (based on timestamps).

Predefined Reports/Views: To make data easily accessible for users, predefined views or reports (e.g., flux measurements over a given period or specific environmental conditions such as heat waves or major storms) can be offered.

3.3.6 Data Visualisation and User Interface

Web Interface: A user-friendly web interface can visualise the data, offering time-series graphs, maps of flux data, and other relevant metrics.

Dynamic Plotting: Data visualisation tools can be integrated to dynamically show real-time data and long-term trends.

Data Export: Tools to export datasets into CSV, JSON, or other formats are important for users wishing to conduct further offline analysis.

3.3.7 Integration with External Data

Climate Data Integration: Integration with external climate databases (e.g., satellite-based data, weather station data) could enhance the analysis by providing additional context to flux measurements.

Interoperability: Standardised formats (e.g., NetCDF, HDF5) for sharing data across systems, allowing easier collaboration between research institutions and environmental agencies.

3.3.8 Maintenance and Monitoring

Database Monitoring: Tools for monitoring the health of the database (e.g., server load, database performance) and logging errors for troubleshooting.

Automated Updates: Schedule regular data uploads from field sensors, with scripts to fetch new data at regular intervals and update the database in real-time.

The success of the infrastructure depends on how well it handles large volumes of real-time, time-series data, integrates metadata, supports various analysis tools, and provides an easy interface for both technical and non-technical users. The management of this digital infrastructure should be managed by one organization agreed on by the consortium.

3.4 Data management, analysis and modelling

3.4.1 Data analysis

The RI should have a data management portal that offers services for visualization and analysis of data. The data infrastructure should be an open data platform allowing all the relevant stakeholders to access and use the data. For convenience, the processed data should be grouped according to the RI themes. In addition, embedded reporting tools in the portal should allow for the generation of regular reports based on processed data. There should be a standardised way of handling data across all the carbon observation RIs. The diagram below shows a possible standardised way of handling data.

3.4.2 Modelling and Remote Sensing

The RI should make use of climate model output for areas where true observations are scarce. Models should be used to collect data that covers a large area, especially because in-situ observations are generally point observations. In-situ measurements should be used to verify the model data. In-situ data should have the capacity to verify the climate models.

The in-situ data is an essential resource in improving model parameterisations and the verification of the model outputs. Similarly, the in-situ observation data plays a similar role for the development of remote sensing algorithms and the verification of remote sensing products at various scales.

3.4.3 Data storage or repositories specifically for the Modelling and RS data outputs

Copies of all data products handled by the data management should be stored in a safe, long-term manner in the infrastructure repository. The data stored should always follow the FAIR principle; Findable, Accessible, Interoperable and Reusable. All the datasets archived or published should always be accompanied by the metadata. Data infrastructure should ensure that there is sufficient data archiving capacity, in the example of the carbon exchange systems deployed in South Africa approximately 50 GB of raw data is produced per station each year.

3.4.4 Data sharing and reuse

To successfully manage the data, the RI should have a license in place that users will have to agree to its terms and conditions. The license should allow the users to share and adapt the data under certain terms and conditions, e.g., Creative Commons. The terms and conditions of the license should emphasize the use of proper reference and citation of the data. Users should also inform the providers when they have used the data for publication. Users should not use the data for commercial purposes.

3.5 Knowledge management and skills building

3.5.1 Knowledge exchange

One of the key roles of RIs is to enable the dynamic exchange of knowledge among researchers, policymakers, industries, businesses, and the public. Effective knowledge sharing drives innovation, translates research into real-world applications, enhances RI performance, and promotes a culture of openness and collaboration. This exchange can take various forms, including discussions at conferences and workshops, engagement on online platforms, training programs, outreach initiatives, participatory approaches, and the development of policy recommendations with opportunities for feedback and dialogue. RI should have outreach programs that involve school and community visits to educate people about the RI and share its outputs.

3.5.2 Knowledge preservation

RIs can implement structured and deliberate strategies to preserve and manage the outputs, data, methodologies, and intellectual contributions produced through their activities. This effort is essential for ensuring the long-term accessibility, usability, and integrity of these resources, thereby supporting ongoing scientific progress, expanding knowledge, and strengthening the reliability of climate-related actions.

3.5.3 Skill development or capacity building

Everyone that is responsible for operating the RI should be trained, that would improve the quality of data and reduce available room for data-associated errors. Data curators should also get training on how to manage the data. This means there should be regular training as equipment and technology are known to change with time. Users should also be trained on how to access and use the data.

3.5.3.1 Scientific capacity

The expertise and knowledge base for researchers and academics to use the RI effectively include training in interdisciplinary fields such as biogeochemistry, ecology, climate and atmospheric sciences as well as appropriate statistical, computational and modelling skills for handling and analysing large data sets. A comprehensive approach that incorporates multidisciplinary education, specific training programs, and improved data science abilities is needed to build scientific capacity for researchers to use the RI within this field and across disciplinary fields. This includes providing training in statistical analysis, and big data management in addition to training in biogeochemistry, ecology, and data analytics through modular workshops, online courses, and certificates. While promoting collaborative research networks through cross-institutional projects and conferences fosters information sharing, joint degrees, research fellowships, and internships can develop multidisciplinary expertise. Researchers are also guaranteed to be prepared to use RIs efficiently if they invest in practical RI training, provide thorough guides, and receive soft skills training in project management and communication. Tertiary education institutions should be actively engaged as actors/stakeholders to promote the uptake of RI use and knowledge generation through analytical and modelling skills development in relevant course curricula.

3.5.3.2 Technicians and Technical capacity

Skills and capacity development are needed in two broad areas: 1) the operation and maintenance of equipment like eddy covariance flux towers, meteorological sensors and 2) the digital infrastructure to support researcher and data product dissemination.

Utilising a community of practice approach the operators of the various sites in the Research infrastructures should arrange regular training.

3.5.3.3 Data curators

Developing expertise in the management, quality assurance, and long-term preservation of research data. Key areas for development include:

- Training in international data standards such as FAIR (Findable, Accessible, Interoperable, Reusable) principles;
- Skills in building, managing, and maintaining relational databases for storing large datasets;
- UX design (user experience design) and UI design (or user interface design) experience to improve the interactions between users and data products.

3.5.3.4 Product users

Promoting integrated scientific, technical and data management skills will help ensure the use and sustainability of the RI and foster innovation on the continent which combined will enhance our responses to climate and environmental challenges.

3.6 Users and collaborative networks

3.6.1 Stakeholder, actors and community

All the interested and affected stakeholders should be involved. Their roles and responsibilities should be clearly communicated.

3.6.2 Stakeholder actors and community engagement

This section is similar to the co-concept section. There should be stakeholder engagements such as conducting workshops, interviews, one-on-one where the outcomes of the RI will be shared. These engagements could improve the knowledge of the stakeholders. the focus here is on the continuous engagement with the user and stakeholder community, with the focus on sharing the information and knowledge that has been developed and encouraging the use of the RI to further the scientific output of the scientific community or encourage the use of data and data products by the environmental management community or commercial use by commercial partners.

3.6.2.1 Feedback mechanisms

Stakeholders should be given a platform to comment, suggest, and evaluate the RI. There should then be a systematic way (whether it’s interviews, workshops, surveys etc.) of responding to their comments and suggestions. This will ascertain stakeholders that their voices are heard and taken into consideration and thus promoting trust and long-lasting relationships.

3.6.2.2 Dissemination and accessibility

The RI outputs should be disseminated in various ways available. For example, publication of research papers. Publication of reports, policy briefs, newsletters and social media posts. The use of local languages should be promoted especially in the local newsletters. This will enable the outcomes to reach all the relevant stakeholders.

3.7 Government and compliance

3.7.1 Standards, policies and ethical consideration

There should be a set of principles, guidelines and practices that govern the planning, development, operation and dissemination of RI activities, with good ethical practices. In the stages where, human engagement is required especially the community members, ethical clearance should be obtained. The outputs should meet the government standards for each theme.

3.8 Citizen Science and Community based Observations

Following the lessons learned the Resilience Academy and other similar organisations - as demonstrated in Pilot 2.4 there is considerable advantage that can be gained from incorporating citizen science and community-based research and science activities into the operations of the infrastructure. There are a number of examples where this can be demonstrated.

The GLOBE (Global Learning and Observations to Benefit the Environment) Program is an international science and education program that focuses on promoting scientific literacy and building connections between people passionate about the environment. GLOBE has three primary goals: increasing environmental awareness, contributing to increased scientific understanding of the Earth and supporting improved student achievement in science and mathematics. By participating in GLOBE, students, educators, citizen scientists, and researchers can connect with the program's global community.

GLOBE learners also investigate and study Earth System Science through their own research projects and those led by NASA. These projects can centre around one of GLOBE's various protocols, campaigns or other initiatives. By participating in these initiatives, GLOBE community members are inspired to collect, submit and analyse GLOBE measurement data from around the world.

With the support of NASA and the federal science agencies that sponsor GLOBE, namely the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF) and the U.S. Department of State (DoS), GLOBE engages learners in the scientific process and advances scientific literacy and science diplomacy. Through GLOBE's community engagement, the program serves as a bridge between the researchers of today and those of tomorrow.

4 Atmospheric composition observation research infrastructure

This section refers to the development of a continental RI that focuses on the observation of atmospheric composition. Atmospheric composition is the driving force of climate change and has significant impacts on human health through atmospheric pollutants. The main greenhouse gases (CO_2, CH_4 and N_2O) are well mixed in the atmosphere, thus local and global fluxes to and from the atmosphere are strongly connected. Greenhouse gas emissions and land use change (from deforestation, degradation and the intensification of urbanization and agricultural activities) are contributing to changes in atmospheric composition and climate change (Hayman et al. 2024).

4.1 Foundational Characteristics

4.1.1 Theory of change

Many of the international atmospheric composition RIs are dedicated to high-quality observation networks that measure anthropogenic pollutants, GHGs and other trace gases that affect the earth system. The establishment of atmospheric composition stations would close apparent gaps in the global air composition monitoring network. A network of atmospheric composition stations will help to understand the constituents of gases in the atmosphere. The information of these components or gases is crucial to reduce air pollution and related adverse effects on health and ecosystems (Pappalardo 2018). The data from atmospheric composition observations networks would enable to track and quantify land-atmosphere-ocean feedbacks and solve the air quality chemistry and physics at a regional and global scales (Kulmala et al. 2023). The data provided by the stations can further be utilized in future climate change scenarios (Labuschagne et al. 2018), contributing with key information for policy-relevant atmospheric products and translating them into mitigation action through policymakers.

However, considering the conditions in the continent and the capabilities (financial and in terms of capacity, technical and support) an appropriate network may require a hybrid of both the high precision and low-cost sensor networks which to balance the necessity to increase the observational density and maintain a support system for quality and traceability. The correct design of this network should include the complementary use of high- and low-cost instrumentation. While high-cost instruments serve as reference providing high-quality and traceable information (which can be considered hubs for technical capacity-building), low-cost instrumentation is mostly based on indirect techniques, being affected by shorter operational life and providing information with lower accuracy. Co-location experiments are known to serve as a quantitative verification of the low-cost sensor performance under different environmental conditions (Malings et al. 2024).

Currently there seem to be a number of networks focused on GHG observations, reactive atmospheric chemistry observations and air quality (which has an implicit human health focus).

The methodologies deployed and site selection criteria for these are different between the existing Atmospheric composition networks, the GHG observation sites are typically located in background sites, the atmospheric pollutant observation sites are located in sites to identify ground-level hotspots for criteria pollutants in order to understand the drivers and magnitude of human health impact and to inform emission control activities and informs urban planning It will therefore be necessary to plan around how to integrate them or to develop independent focused infrastructures that are inter-comparable and linked.

4.1.2 Products, solutions and outputs

The proposed RI should produce its outputs in different forms. There should be publications by researchers using the data from the RI, with transparent reporting about data design and evaluation essential to build the confidence of end-users (Malings et al. 2024). The data from the observation networks should enable researchers to answer research questions, and communicate those findings through research papers, conference presentations, workshops etc. All reported data should contain sufficient metadata consistent with FAIR principle (Lewis, von Schneidemesser, Erika, and Peltier, Richard J. 2018; Malings et al. 2024). The outputs of the RI should also enable the government to make informed decisions with regards to atmospheric composition from Africa. Those decisions can be communicated via direct policy input or the provision of facilities for conducting targeted research into specific areas of concern. Moreover, the outputs should also be communicated in any form (such as booklets, newsletters etc.) to all the interested actors and stakeholders. (https://ndacc.larc.nasa.gov/instruments/ftir-spectrometer)

4.2 Impact pathways

Systemic long-term atmospheric observations form the backbone of quantification and understanding atmospheric change, tracking background variability, predicting the extreme events and its impacts, improving representations of future climate scenarios, and ultimately informing policies to address environmental issues. When these observations are well coordinated, it can be assimilated into emissions models and global earth system models which, in combination with understanding the underlying processes, can improve the accuracy and uncertainty associated with these models. These observations are typically well coordinated in industrialised countries, and less so in developing countries. Improved coordination of observations in data sparse regions will not only improve regional quantification of uncertainties, but also the global atmospheric composition and its processes.

4.2.1 Co-design

The relevant or interested stakeholders should be involved in the planning and design of the infrastructure in a cost-effective way and accounting for socioeconomic and technical factors. Where possible existing infrastructure and networks should be incorporated to explicitly develop the linkages between the components and observation types. This entails planning where the collaborative network of observation sites should be deployed (bearing in mind existing observation networks), what the key variables to be measured are and why they need to be measured. It requires the participation of multiple stakeholders (researchers, policy makers and technology experts throughout the planning and execution, and promotes trust and transparency, and promotes partnership and buy-in from all collaborators. A key starting point for the selection of essential variables for atmospheric composition are the GCOS essential Climate Variables particularly those relating to atmospheric composition including Aerosols, CO_2, Methane and other GHS, Ozone and precursors for aerosols and Ozone (WMO 2015; Reyers et al. 2017; Lopez-Ballesteros et al. 2018), who is going to finance the RI Co-design minimizes the chances of missing crucial components of the RI. It promotes trust and transparency and promotes partnership and buy-in from all collaborators.

4.2.1.1 Ground based measurements and measurement traceability.

The atmospheric composition RI should adopt the six focal points addressed by the Global Atmosphere Watch Programme (Schultz et al. 2015). The six areas include GHG, ozone, aerosols, reactive gases, total atmospheric deposition and solar ultraviolet radiation. In addition, it should look at examples of existing networks in establishing a coordinated community where internally consistent processes and procedures (standardised operating procedures, traceable calibration processes) are followed to ensure compatibility in the network.

4.2.2 Data analysis

Data should be stored in a reliable database and analysed using the appropriate analysis tools. Mention tools that are usually used for each data. These include standardised quality control procedures which can ensure data quality are validated and treated in a systematically consistent manner.

4.2.2.1 Validation

Satellite observations of atmospheric observations provide a generalised perspective representing a much higher spatial and temporal scale than in situ ground based observations. Most satellite observations are validated using surface observations from industrialised countries where in situ observations are more prevalent. For example, ambient PM2.5 concentrations can be estimated using MODIS Aerosol Optical Depth (AOD) using data from the AERONET aerosol network, with limited validation sites in Africa. AOD is a measure of light extinction by atmospheric aerosols, enabling AOD to be a predictor of ambient PM2.5. Estimates of PM2.5 concentrations from satellite data can be used to identify air pollution hotspots, health effects studies and air pollution trends. The in-situ measurements of air pollution can then be used to validate the satellite data estimates. Data generated through an expanded ground-based observations network would improve validation of remote sensing data.

4.2.3 Dissemination of information

It is highly encouraged that data should be openly and freely accessible in the data portal of the managing organization. Information should be disseminated in all applicable ways (i.e. research papers, conferences, workshops, newsletters, booklets etc.). It is also important that data providers are always acknowledged when data is used.

4.2.4 Training on usage of data

If the RI is managed by a consortium from different organizations, each organization should make it their responsibility to train the data users on how to use the data. Inadequate knowledge on how to use the data may result in the misuse and misinterpretation of the data. There should be a standard data use course across all the organizations that will be conducted annually. The provision of standardized open access tools such as scripts for data analysis should be provided through a centralised repository.

4.2.5 Equip stakeholders with knowledge

All the knowledge obtained from the RI should be equally shared with the stakeholders. The knowledge should help the stakeholders to address the issues they are facing.

4.3 Monitoring, Evaluation and Learning of Impacts

The impact of the RI should be regularly monitored. This involves bringing together the stakeholders to revise what was said to be the goal of the RI. The stakeholders should use a set of indicators to evaluate the goal or objective of the RI. Participatory Monitoring Evaluation Reflection learning (PMERL) is a tool that is often used to monitor the activities. This tool can be adopted to monitor the impact of a RI. The tool is self-explanatory, meaning after stakeholders have participated in the development of the RI they should be involved in all the following steps which are monitoring, evaluation, reflection and learning. PMERL gives an opportunity to improve the performance of the RI.

4.3.1 Co-concepts

In every step of establishing the RI, co-design, creation, production is critical. All the relevant or interested stakeholders should be involved in every step; from planning of the RI to finally disseminating the product or output. There should be clear understanding who is involved in which stage if not all. It should be considered that some stakeholders will join at the later stages.

4.4 Observations, data sources and technologies

4.4.1 Observations, measurements and monitoring

For a RI in support of atmospheric research, sites to deploy the network of measurement instruments should be carefully selected based on the criteria of supporting equitable, decentralized data collection. These sites can be fixed monitoring sites (which can serve as hubs for technical capacity-building) but also mobile platforms and broader networks of low-cost sensors. Instruments of the different focal areas can be deployed in one site depending on the needs of that particular site. Stations should ideally be distributed across African countries because the contribution of GHGs and other trace gases in each country are crucial. The two reviewed existing atmospheric stations in Africa are deployed in mountainous terrains and or close to the ocean (Mt Kenya in Kenya and Cape Point in South Africa). However, regions that are hotspots of air pollution should also be prioritized including with a focus on atmospheric pollutants and urban and industrial GHG measurements and Short-Lived Climate forcers. The information will enable appropriate air pollution and GHG mitigation strategies. The stations could be deployed in the same region as the stations for other RIs such as carbon exchange observation RI. This would promote collaboration between the various RIs or components of the RI. The outputs of the RIs can be linked to determine the possible linkages between the outputs of the RIs. Appropriate planning and the judicious use of developing technologies in the low-cost sensor space and the spatial coverage of remote sensing applications needs to be considered. Air quality and GHG monitoring should be accompanied by meteorological measurements in order to support the interpretation of vertical and temporal concentration variables (Dvorská et al. 2015) and access the opportunities presented through the recent developments in machine learning and AI technologies.

The review or auditing of existing RI should first be done to obtain the spatial distribution of the existing networks. This will form part of this concept in the upcoming deliverables. A mix of new high precision stations and networks of appropriately managed low-cost sensors should then be deployed where there are gaps and the spatial integration capabilities of RI products and applications should be incorporated. In addition to identifying optimised locations for new RI, the exact location of the proposed RI should be determined by the practical considerations such as topography, presence of existing infrastructure, also identifying local expertise and institutions for long-term support. The WMO Observing Systems Capability Analysis and Review Systems Tool (OSCAR) contains defined requirements for the observation of physical variables in priority areas of the WMO and the GCOS essential climate Variables on Atmospheric Composition. Lopez-Ballesteros et. al. (2018) provide a useful summary of the essential variables that should be considered in different themes of an RI. To avoid gaps in data, the stations should be regularly maintained by trained personnel to produce quality data. Long-term quality data enable the detection of trends.

4.5 Current status of observations

4.5.1 Greenhouse gas observations

Africa's role in the global greenhouse gases (GHG) cycle is of great interest due both to the large landmass covered by the continent, and the potential for rapid change in coming decades as the human population increases and land use patterns continue to evolve. Africa contains some of the largest tracts of untransformed land in the world, although it is often heavily utilized for grazing, fuelwood and other natural resources. With a current population of about 1.4 billion, set to increase to over 2 billion by 2040 (United Nations Urban Settlement Programme, 2019), it is expected that large areas of land will be converted for agricultural production to feed this increasingly urbanized community and to increase the country-level GDP. Concurrently, there is massive interest in using African landscapes to store carbon and offset global carbon emissions (Armani et al. 2022). It is therefore imperative to develop reliable data on key carbon-cycle processes and GHG emissions to quantify the net effect of these competing trends (Ernst et al. 2024).

In thinking of this RI to support atmospheric composition observations we have included both the observations of Greenhouse Gases such as those undertaken by the GAW program that typically focus on the long-term concentrations in the background atmosphere and the observations that typically fall under the auspices of air quality monitoring and that may include some climate relevant atmospheric pollutants (Short Lived Climate Pollutants). The joining of these aspects was done since there are a lot of technical similarities, including the principles of operation of the instrumentation, the calibration and maintenance requirements and the technical capacity of the operators, the major differences will be issues of location and specific instrumentation models.

Currently the GHG observation Network in Africa is quite limited. Figure 5 shows the location of planned and current Global Atmospheric Watch Sites, with three long term observation sites on the continent, those being Assekrem/Tamanrasset (Algeria) in the Sahara, Mt Kenya in East Africa and Cape Point in South Africa. Additional observatories in the oceanic islands surrounding the continent are located at Cape Verde, Amsterdam Island, Tenerife (Canary Islands Spain) and La Reunion (France).

Associated with the GAW program there are a number of sites that focus on atmospheric deposition, through the INDAAF program in Africa these include 6 sites in West and Central Africa, 4 historic sites in South Africa, that are currently being redeveloped through the EFTEON Network

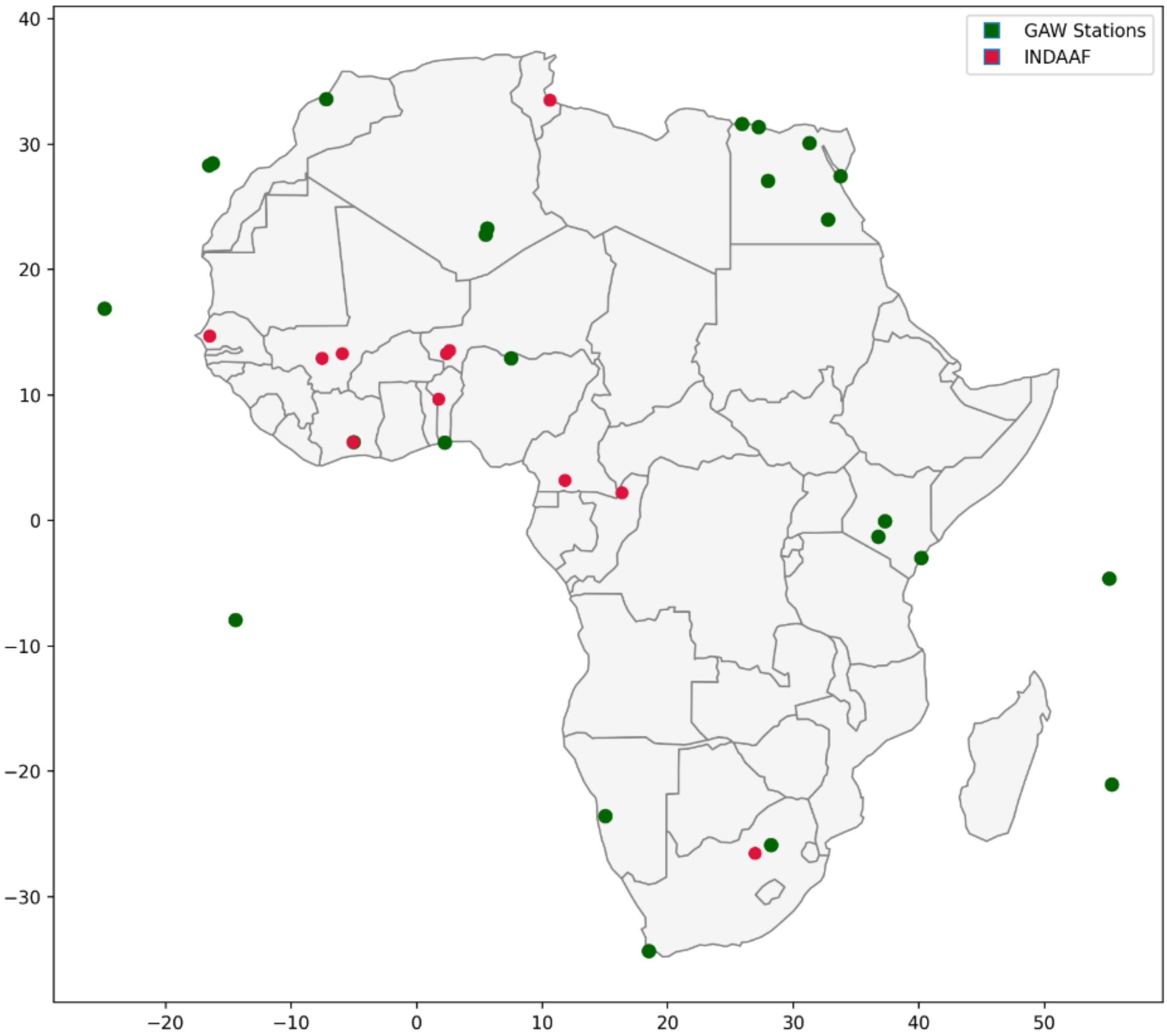

Figure 5 GAW and INDAFF sites in Africa

An in-situ atmospheric greenhouse gas observation network design for Africa has been described by (Nickless et al. 2020) as part of the SEACRIFOG project which was a precursor to KADI. It provided optimal locations to situate new atmospheric monitoring sites to an existing network to reduce the overall uncertainty of CO_2, CH_4, and N_2O fluxes from terrestrial Africa, where 2012 has been taken as a representative year. Further developing a continental atmosphere network should be guided by users, namely modelers and specific challenges, e.g. regional GHG flux calculations (e.g. for the Congo basin, Eastern Africa etc.).

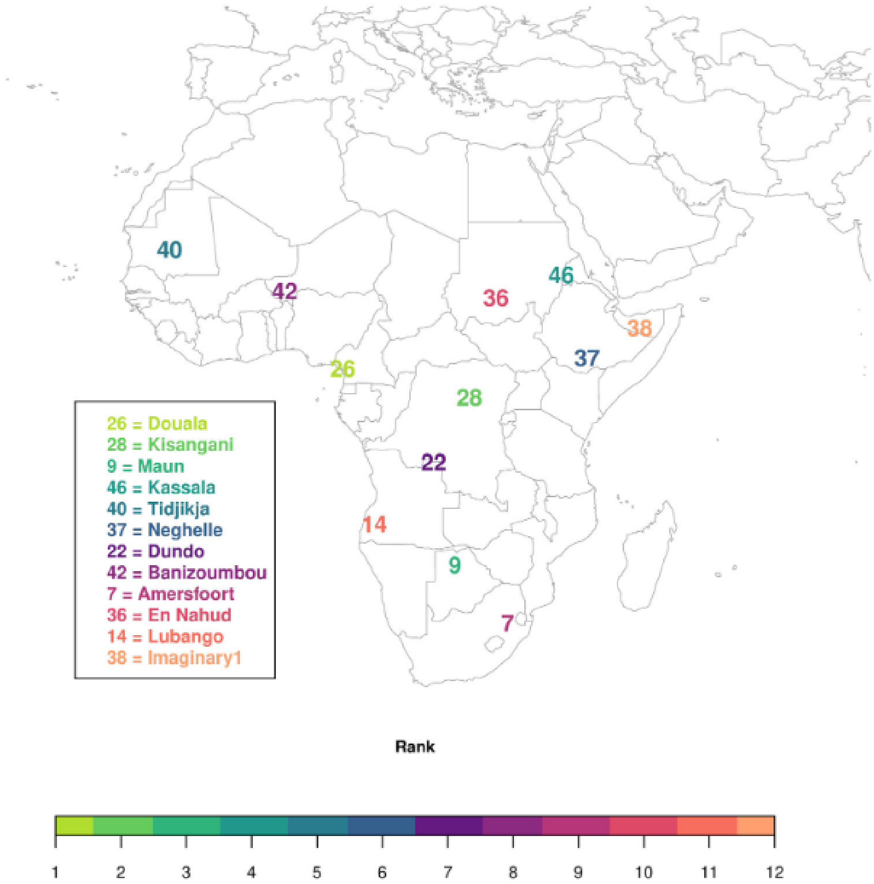

Fig. 11. Optimal locations to situate new atmospheric monitoring sites to an existing network to reduce the overall uncertainty of CO_2, CH_4, and N_2O fluxes from terrestrial Africa, where 2012 has been taken as a representative year, following approach 2, which optimised over the three gases simultaneously. Sites are coloured according to the rank in the optimal design, with light green sites representing the site with the largest uncertainty reduction and which is the first site added to the network.

Figure 6 Optimal location for new GHG observations from the (Nickless et al. 2020) study

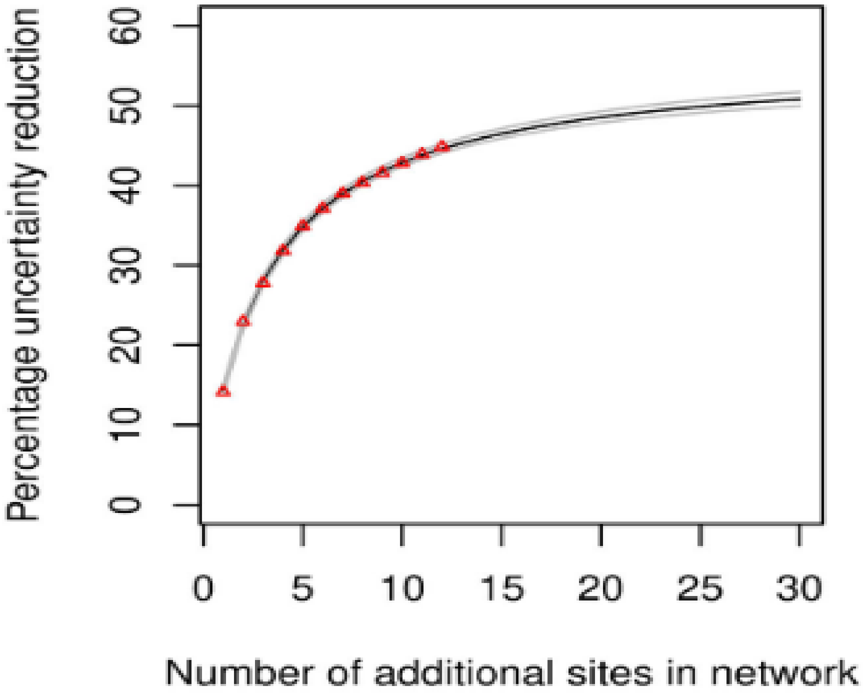

Figure 7 Uncertainty reduction with the inclusion of each additional observation site in Africa (Nickless et al. 2020)

4.5.1.1 The Global Greenhouse Gas Watch (G3W)

The WMO has since 1989 implemented a coordinated Global Atmosphere Watch programme for continuous long-term background monitoring of atmospheric composition. To strengthen research components and continuous support and improve operational infrastructure, the Global Greenhouse Gas Watch (G3W), aims to provide global fields of net fluxes of the main GHGs, through a surface based observation network, improved exchange of satellite-, aircraft and surface based observations, collaboration on common standardised methodologies and practices for GHG modelling and data assimilation, common file formats and practices, common verification and validation methods and common post-processing procedures and downstream applications. G3W will provide a comprehensive monitoring framework of GHG and thereby address the urgent need for information that helps to understand and assess the impact of mitigation actions taken by the Parties to the United Nations Framework Convention on Climate Change (UNFCCC), and the Paris Agreement on the state of climate. Such information will be produced in a timely manner and will take into consideration both human and natural influences on the levels of greenhouse gases in the atmosphere.' (WMO 2024). G3W will comprise four main fields:

(1) A comprehensive sustained, global set of surface-based and satellite-based observations of CO_2, CH_4 and N_2O concentrations, total column amounts, partial column amounts, vertical profiles, fluxes and supporting meteorological, oceanic, and terrestrial variables, internationally exchanged as rapidly as possible, pending capabilities and agreements with the system operators.

(2) Prior estimates of the GHG emissions and absorption based on activity data and emission factors, and process-based models and their uncertainties.

(3) A set of global high-resolution Earth System models representing GHG cycles.

(4) Data assimilation systems (associated with the models (item 3)), that optimally combine the observations with modelling

The G3W Implementation Plan foresees an initial operational phase from 2028 on. This document outlines a potential African contribution to the G3W according to this plan. The G3W aims to bring together all observing systems, including modelling and data assimilation capabilities, to ultimately reduce the uncertainty in assessing efficacy of climate action. Monitoring networks globally (including in Africa), would ultimately feed into the G3W network.

4.5.1.2 Global Atmosphere Watch (GAW)

The recognized need for improved scientific understanding of the increasing influence of human activities on atmospheric composition and subsequent societal impacts resulted in the establishment of Global Atmosphere Watch (GAW) programme in 1989 (Moreno, 2023). The program originated from the build-up of a global network of background stations, which remain as the backbone and unique feature of GAW (Schultz et al., 2015). The GAW program itself does not perform the measurements of atmospheric constituents but these are rather carried out by collaborative programs of national hydro-meteorological services, research institutes and universities (Schultz et al. 2015).

Its mission is to provide systematic long-term monitoring of atmospheric chemical and physical parameters globally. The programme has six focal areas which include GHG, ozone, aerosols, reactive glasses, total atmospheric deposition, and solar ultraviolet radiation. The network consists of global, regional, and contributing stations and according to Moreno (2023), there are 31 global stations of surface base observations, approximately 400 regional stations which measure various observations of GAW parameters and around 100 contributing stations. The observations are linked to common reference standards and the observational data are made available at 7 designated world data centres (WDC) (Moreno, 2023). The programme has quality assurance and quality control systems whose objectives are to ensure that the data in the WDCs are consistent, of known and adequate quality.

Within the Global programmes and independent, there are a number of observatories in Africa that will need to form the skeleton of an integrated observation network, these include the GAW observatories at Cape Point (Morgan et al., 2015; Venter et al., 2015) and Mount Kenya (Henne et al., 2008; Kirago et al., 2023) , the Mount Mugogo Observatory in Rwanda (Andersson et al., 2020; DeWitt et al., 2019).

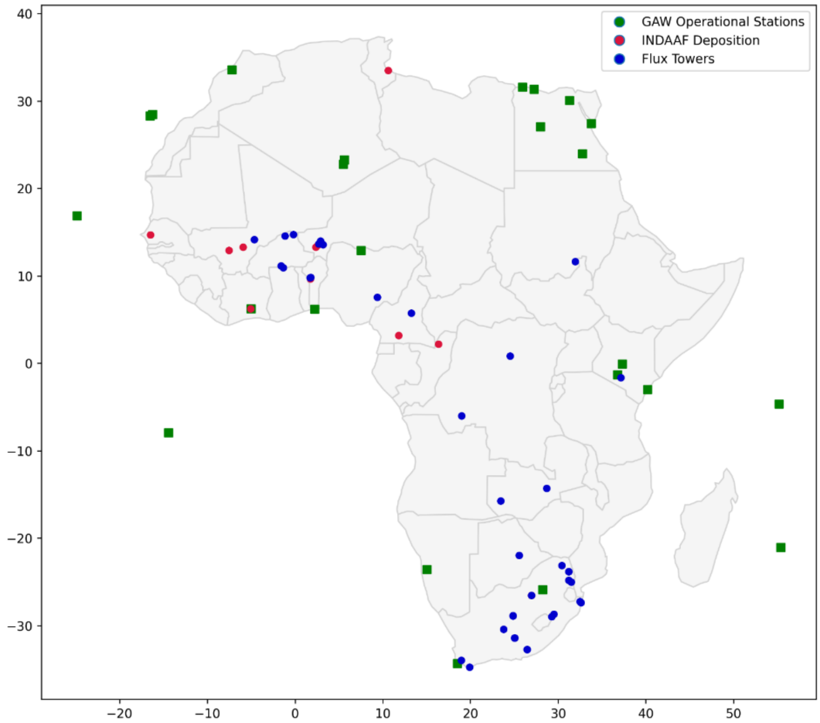

Figure 8 Observational network of currently operational atmospheric concentrations, flux tower, and atmospheric deposition stations throughout Africa. Global Atmosphere Watch stations taken from WMO GAWSIS, Flux towers compiled from published data, and deposition stations from INDAAF programme.

The WMO Global Atmosphere Watch measurements guide (WMO GAW report 143) provides an overview of the requirements GAW observations. It describes the technical requirements for the following:

- Greenhouse gases (carbon dioxide, CFCs, methane, nitrous oxide, tropospheric ozone)
- Ozone (surface, total column, vertical profile by both ground-based and satellite)
- Solar radiation including ultraviolet
- Chemical and physical properties of aerosols including optical depth
- Reactive gases (carbon monoxide, sulphur dioxide, nitrogen oxides, volatile organic
- compounds)
- Meteorological parameters

In decision making for appropriate network design, atmospheric footprints provide useful information which simulates atmospheric transport upstream of regions of measurements. It typically consists of a lagrangian transport model, in conjunction with emissions sector fuel type to highlight the source region of the fuel (or GHG). Along with sensitivity analysis of station density for an optimised observation network, it provides a useful tool to identify where to prioritise locations for new observation stations in sparse data regions.

4.5.2 Column measurements

To supplement the in-situ measurements and to correspond more closely with the satellite derived observations, networks of ground-based atmosphere column observations have been established globally, these include the Total Column Carbon Observation Network (TCCON), the Network for the Detection of Atmospheric Composition Change (NDACC), the Collaborative Column Carbon Observation Network (COCCON), Aeronet and SHADOZ., some (albeit limited) of which are represented in Africa. Within these networks, ground-based Fourier Transform Spectrometers record direct solar spectra in the near- and mid-infrared wavelengths, and provide an accurate and precise column average of the concentrations of CO_2, CH_4, N_2O, HF, CO, H_2O and HDO, among other trace gases (Wunch et al. 2011; Frey et al. 2019). These columnar products are provided within TCCON, but NDACC also gives CH_4, N_2O and tropospheric O_3, as GHGs, reactive gases such as CO, formaldehyde and other atmospheric compounds related to O_3 and ODSs. These provide an essential validation resource for the satellite observations Orbiting Carbon Observatory-2 (OCO-2), OCO-3, the Greenhouse Gases Observing Satellites (GOSAT and GOSAT-2), the Sentinel 5P instrument TROPOMI, and future missions such as the European Commission's Copernicus CO_2 monitoring (CO_2M) mission (Pinty et al. 2019), as well as atmospheric models. Limited ground-based column observations occur over Africa (Figure 9), with only column instrument have been deployed in Morocco in 2024 (University of Marrakech), and another is planned for deployment in Côte d'Ivoire (LAMTO scientific reserve) in 2025 (M.Romanet, pers. comm.). Additional column measurements are required to have a representative distribution of column observations in sparsely measured regions, and are an essential element of a regional observation network. These measurements were performed with the COCCON low resolution FTIR instruments.

Additional measurements have been taken in (https://www.imk-asf.kit.edu/english/3884.php) on shorter term campaigns:

- Gobabeb, Namibia 2017-2019
- Junja Uganda, 2020,
- Cedre Gouraud Forest , Morocco 2019

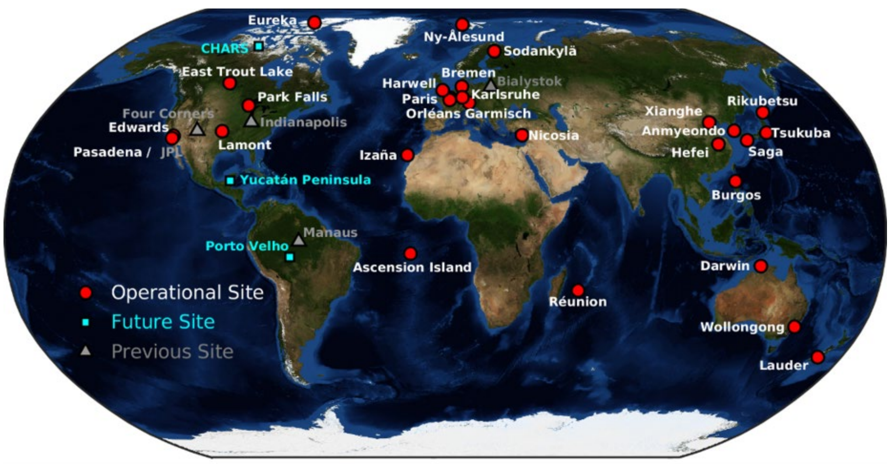

Figure 9 Total carbon column observation network, used for validation of satellite missions of atmospheric carbon concentrations.

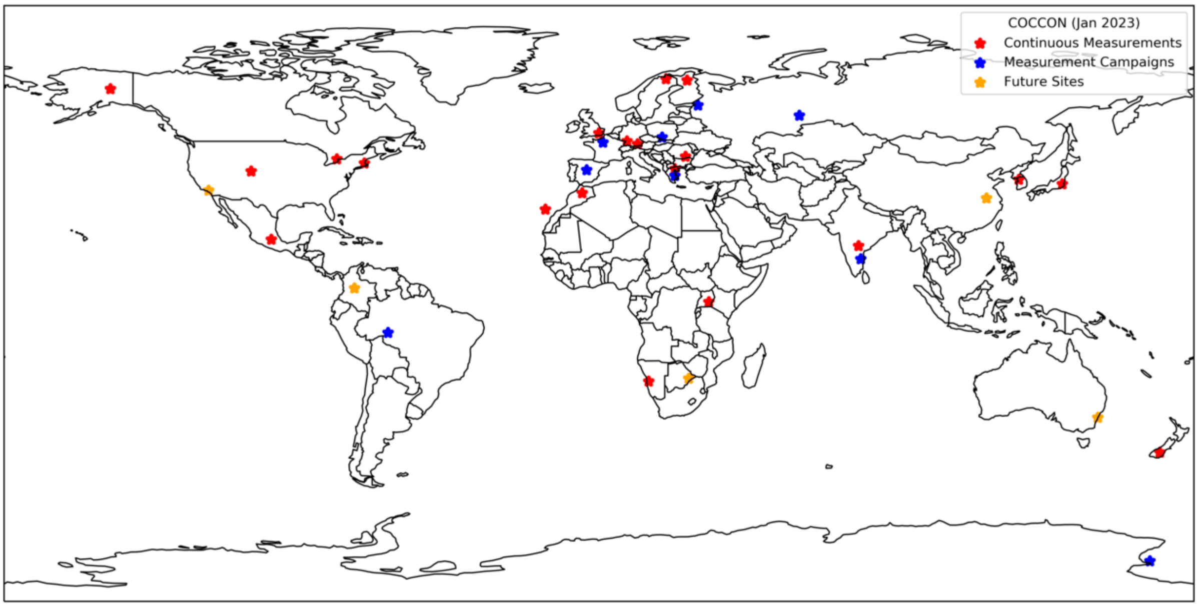

Figure 10 Map of the COCCON measurement sites (https://www.imk-asf.kit.edu/english/3884.php)

4.5.3 Atmospheric deposition measurements

The International Network to study Deposition and Atmospheric composition in Africa (INDAAF, https://indaaf.obs-mip.fr/) is committed to long-term monitoring of atmospheric deposition fluxes in Africa. The network has been operational since 1995 (IGAC-DEBITS Africa) and combined with the 'Sahelian Dust Transect' (2006) of the African Monsoon Multidisciplinary Analysis international program. This program is endorsed by the WMO Global Atmosphere Watch programme, and contributes to the dust and storm warning advisory program. The network has 8 stations in 7 countries of West and Central Africa, and two partner sites in South Africa and Tunisia (Figure 10). In addition, there is a network of Aeronet Sites distributed across the continent (Horowitz et al., 2017), the International Network to study Deposition and Atmospheric Chemistry in Africa Debits Network (INDAAF) and its precursor networks (Adon et al. 2010a; Galy-Lacaux and Delon 2014) for Atmospheric Deposition studies with a network across Senegal, Mali, Niger, Benin, Cameroon, Cote d'Ivoire and Congo and partners in South Africa and Tunisia (Ossohou et al. 2023).

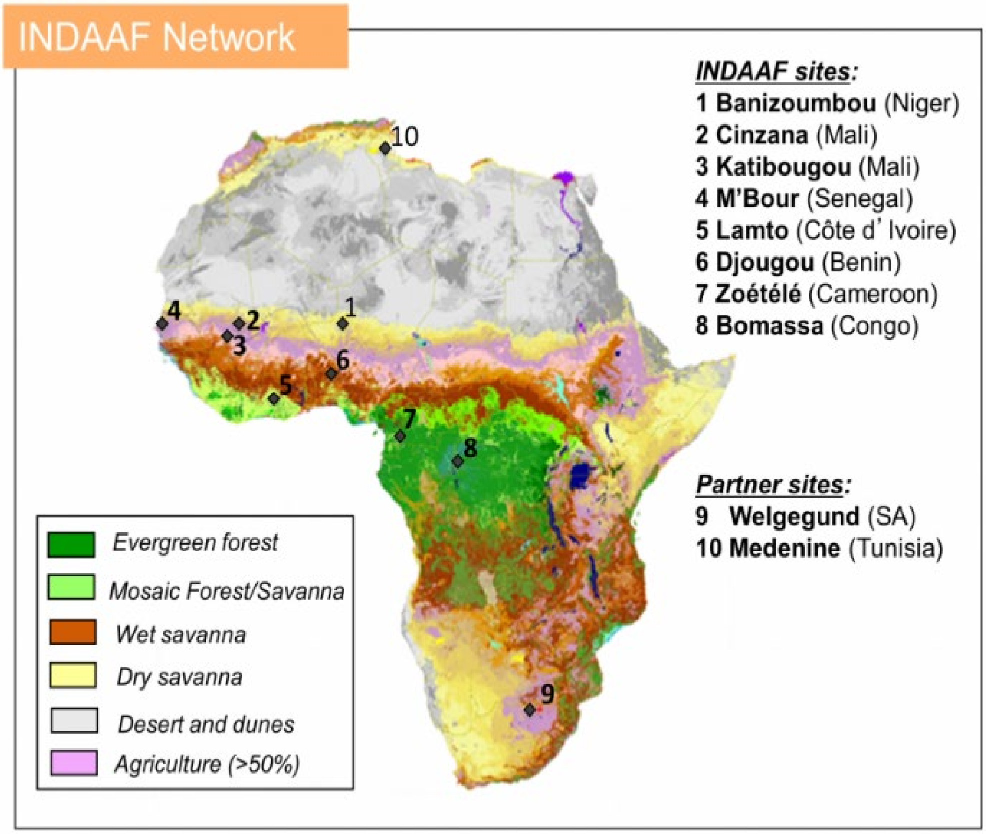

Figure 11 Map of the locations of the Deposition sites in Africa from the INDAAF network

Within the network, deposition fluxes of insoluble atmospheric particles are collected with passive collectors, wet deposition of insoluble particles during precipitation events, precipitation chemical composition, meteorological parameters, trace gases (SO_2, HNO_3, NH_3, NO_2, and O_3) using passive adsorption onto an adsorbent sampler. In addition, aerosol particulate matter ($PM_{2.5}$ and PM_{10}) are collected onto filter papers (quartz and Teflon) using air inlet pumps and characterized by ion chromatography and thermo-optical analysis. Finally, sun-photometers are deployed at these sites for Aerosol Optical Depth measurements which form part of the AERONET network. Expansion of this network would be an easy addition to the monitoring activities, given the relative low cost of the sampling of atmospheric deposition.

4.5.4 Air Quality Monitoring

In the context of this report the observations with a focus on Greenhouse gas concentrations and those related to human health have been included in this infrastructure but they have some differences in approach.

4.5.4.1 Air quality reference stations

There exists a network of air quality monitoring observations across the continent, these include the traditional Air Reference Stations such as the SAAQIS network in South Africa (Feig et al. 2019; Tshehla and Wright 2019; Venter, Cramer, and Hawkins 2019; Garland et al. 2009) and in a limited extent in other parts of the continent. Although the networks are beginning to be developed in Ghana and Cote De Ivoire and a network of lower cost air quality sensors, for example, AirQo has emerged as one of Africa's largest air quality monitoring network based on low-cost air quality sensors, Internet of Things (IoT), and artificial intelligence as novel approaches to improving air quality in urban spaces (Bainomugisha et al., 2023), while (Singh et al., 2021) used a network of optical particle counters to assess the impacts of traffic on air quality in three East African cities. While these lower cost sensors provide an important tool for air quality observations and expanding the networks, care needs to be taken to ensure that the appropriate calibrations and traceability is insured (Lewis et al., 2018; Mead et al., 2013)

Figure 12 cities in Africa with a population of greater than 1 million inhabitants

Figure 13 Map of current Air Quality monitoring stations as reported on World Air Quality Index

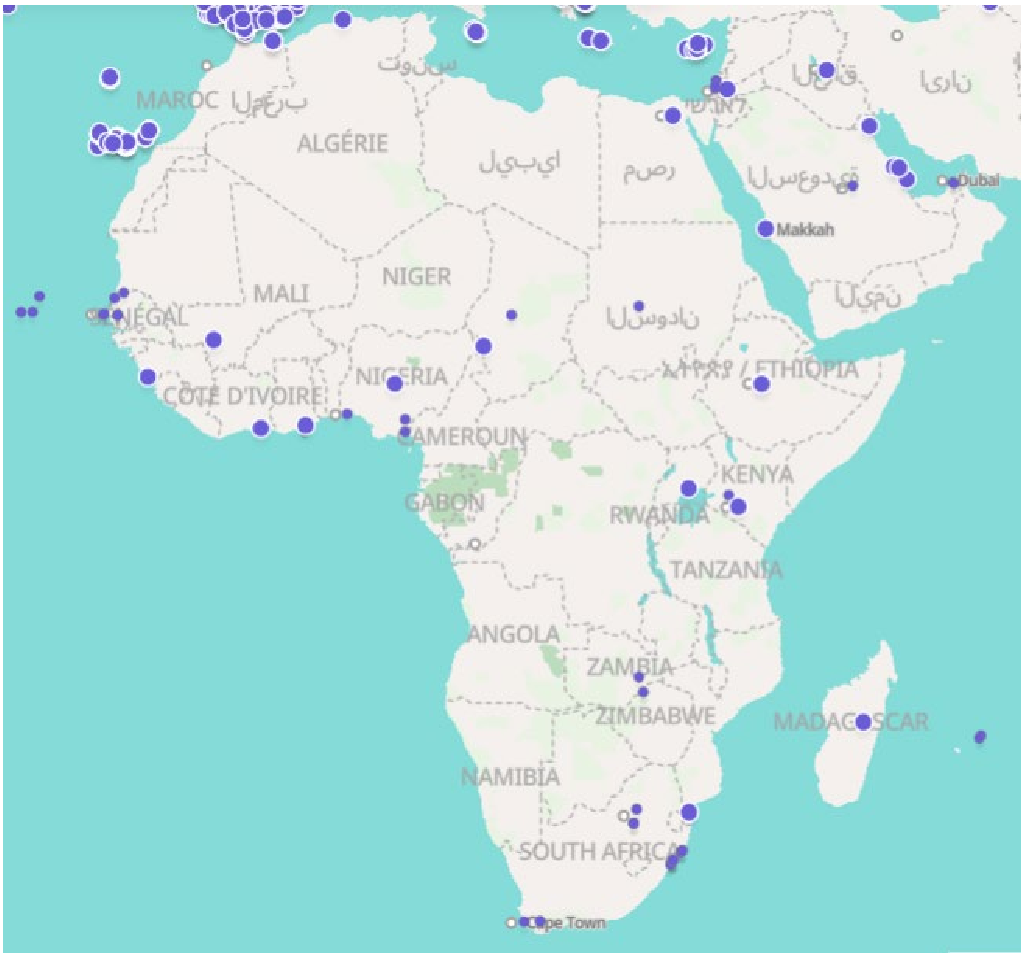

Figure 14 Map of current Air Quality monitoring reference stations as reported on OpenAQ api

At local level, in cities, atmospheric observations should combine air quality and GHG measurements although these are in practice often separate. This would support climate services related to transport as well as services related to air quality improvements. Atmospheric observations combined with inverse modelling could also be used locally to provide verification services for larger natural CO_2 sinks (Nickless et al. 2020; 2019; 2015).

4.5.5 Observation Infrastructure

4.5.5.1 Greenhouse Gas observations

High precision GHG observations are essential for accurate tracking of the global climate system and climate mitigation strategies. These are measured through a global network of ground based observations and remotely sensed measurements. Ground based observations are typically monitored through Infrared Gas Analysers (IRGA) which quantitatively relates the concentration of the GHG to its absorption spectrum. Comparable high precision measurements are achieved through Gas Chromatography where GHGs gas mixtures are separated to its components based on its physical or chemical properties. These instrumentation are often quite labor intensive and expensive to maintain due to its specialised technician requirements.

Finally, most high precision measurements currently are performed using lazer based cavity ring-down spectroscopy where the absorption of light through a lengthy cavity is related to its decay time after excitation. Measurements of this kind often require a substantial effort of data quality assurance. This includes centralised calibration of reference standards, where the entire network utilised similar reference materials. Both the GAW network and ICOS make use of centralised calibration laboratories to provide reference standards for the monitoring stations. In addition, laboratories within the network participate in voluntary auditing of practices and procedures, as well as inter-laboratory comparison studies to objectively ensure the data quality from individual stations

4.5.6 City GHG observations

Tracking urban emissions is a priority for local governments to monitor the impacts of localised climate change and develop effective mitigation strategies. To this end, the World Bank has commissioned a Carbon Monitor for Cities to monitor near-real time city level GHG emissions from various sectors. Local GHG emissions are unavailable for cities in low- and middle-income countries. Downscaling proxy data (for instance EDGAR) to a local grid render these data highly inaccurate, while satellite measurements are often hampered by cloud cover resulting in data gaps. While these data are useful for certain analysis, they are insufficient for high-frequency, city level emissions data.

A top-down inventory approach is often required for local city level emissions inventories. This approach requires the measured concentrations of GHG in the atmosphere, and applying inverse modelling techniques to account for those observed levels. The modelling inversion requires gas concentrations as input to sophisticated atmospheric transport models that simulate how the gases are dispersed, transported and removed from the atmosphere. The emission sources of the observed GHG concentrations are then calculated from the simulated gas dispersions. Although modelling uncertainties of the transport and chemical models affect the accuracy of the inventories, these models are nonetheless useful for independent verification of bottom-up inventories based on sector specific emissions reporting.

4.6 Air Pollutants (Aerosols, Ozone and its precursors, reactive gases)

Air quality monitoring forms a core component of any air quality management plans at the local , regional or national levels. An air quality monitoring network might consist of a number of elements at differing cost points and with differing focal areas, this might include sensors for particular pollutants, primarily focusing of the criteria air quality pollutants such as Particulate matter, for health we typically refer to Particulate matter (size classes of PM10 and PM2.5), SO_2, NO_x (Consisting of the dynamic relationship between NO and NO_2), CO and Ozone (O_3). In association with these pollutant concentrations meteorological parameters such as wind speed and direction, temperature, humidity, solar radiation and precipitation are also measured to provide context to the air quality measurements. A network may observe all the pollutant or if necessary, focus on pollutants of particular relevance the location.

4.6.1 Air Quality Monitoring Plan

Before ambient air quality monitoring is initiated a comprehensive Air, Quality Monitoring Plan should be established. The plan must be informed by the main monitoring objectives and must provide a roadmap on station operation, management and maintenance for a period at least three years and it should be periodically renewed. The plan must also ensure that all ambient monitoring assets are procured, maintained and managed.

The monitoring plan must:

- Identify essential resource requirements for conducting air quality measurements such as manpower, infrastructure in the field and laboratory, equipment and finance.
- Include scheduling of station management, instrument maintenance and calibration for a sustainable operation of monitoring station.
- Provide data acquisition, management and reporting procedures.
- Identify sufficient financial resources to be made available for the operation of the stations, purchasing of new/replacement instruments, hiring of manpower, data management (processing, reporting, archiving) and undertaking laboratory quality assurance and quality control procedures.
- Include a plan to secure adequate resources (staff, equipment, spares, consumables etc.) to undertake the monitoring initiative.
- Present personnel capacity development plans of staff involved in the operation, maintenance, calibration and reporting activities with the necessary training skill, expertise and qualification to undertake the work.

The figure below demonstrates the major steps that should be incorporated into an air quality monitoring plan (Figure 15).

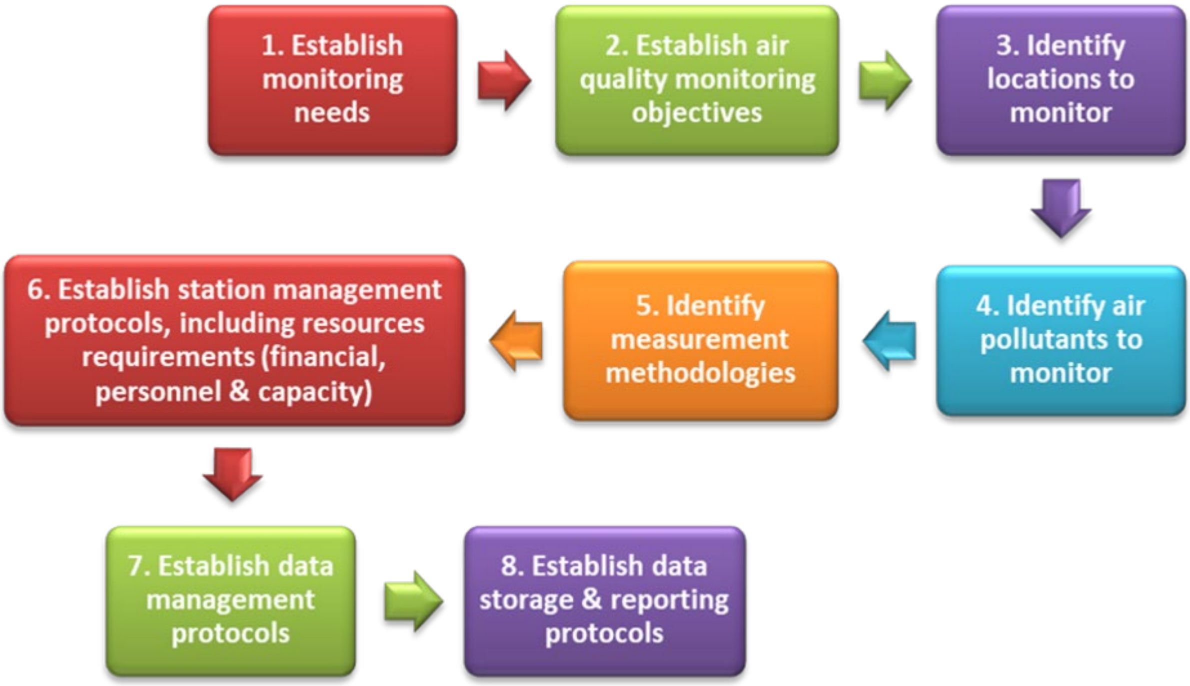

Figure 15 Major steps for establishing an air quality monitoring plan

Step 1 - Establishment of monitoring needs; the first step in establishing an air quality monitoring programme is to carry out a desktop study to ascertain both the current status of air quality and the needs to monitor air quality. An emission inventory study and air dispersion modelling may be carried out as part of the desktop study or used if information is available. This study identifies emission sources and pollutant types, describes the meteorology in the region, including issues such as the predominant wind directions, the presence of inversion conditions or other systems that impact air quality. the location of areas of particular sensitivity to air pollution, such as schools, hospitals or sensitive ecosystems, and population. factors relating to the geography of the area, including the land use, the topography. In areas where ambient air quality levels are relatively unknown, a simpler sampling study may be carried out for reconnaissance purposes, using passive samplers or low-cost sensors.

Step 2: Establishment of the Air Quality monitoring objectives; based on the outcomes of step 1 the monitoring objectives need to be established. The main objectives of ambient air quality monitoring are typically; determine air quality in a region and assess its effects on human health and the environment, provide information fundamental to decision-making and to evaluating the efficacy of air quality management strategies. Air quality monitoring gives evidence on the current levels of pollutants and provides policy-makers with information on how to better manage air quality in their regions.

Step 3 Specify Locations to monitor: The principal factors governing the location of a monitoring station must be based on the objectives of monitoring. The siting of an air quality monitor has a profound effect on the resulting measurements of pollutants and on achieving monitoring objectives. Things to consider include:

- The monitoring network design and station siting. the concentrations of an atmospheric pollutant detected at a site are a result of a combination of a set of processes, including the emissions of the pollutants, advection and vertical mixing, chemical transformations and deposition. In siting the stations consideration needs to be taken of Spatial and temporal representativeness of the monitoring site. The monitoring should be not located where significant interferences are present or anticipated. the site should be physically appropriate in that it should be available for a long period of time, there should be access and functional issues such as electricity, data signal and security should be in place.

- Classification of the site: a standardised site classification system should be established, in Table 1potential site classifications and their characteristics are presented.
- Included in the development of the site should be the appropriate metadata, including the location, the land use, contact details et cetera

Table 5 Classification of air quality monitoring sites

Site Classification	Characteristics - sources and spatio representation
Industrial sites	Microscale representation, sources linked to the local industry, may include PM, and other pollutants dependent on processes
Mining Sites	Microscale representivity, sources related to mining activities, primarily PM
Urban Sites	Macroscale, a combination of sources from local activities including vehicles, small industries, and potentially waste burning
Peri-urban sites	Macroscale, a combination of sources from local activities including vehicles, small industries, and potentially waste burning
Suburban Low income	Macroscale - residential sources including solid fuel combustion, waste burning and vehicular emissions
Rural high-density sites	Macroscale- residential sources including solid fuel combustion, waster burning, agricultural activities
Remote background	Macroscale- representative of the background atmosphere and regional sources
Others	

Step 4: Identification of the pollutants to monitor: based on the known and expected emissions that will impact the site the prioritisation of the monitoring should be done, with a priority on the pollutants that are expected to have the greatest impacts.

Pollutant	Criteria for locating the monitoring site
SO_2	Sources of SO_2 include industrial emissions, diesel vehicles and domestic emissions from fossil fuel burning. natural sources include volcanic activity
NO_2 (and NO_x)	NO_2 is formed in the atmosphere by reaction of nitric oxide (NO) with ozone

	and hydrocarbons (HC). Thus, high NO_2 levels are expected at locations where NO, ozone and hydrocarbons levels are high. Generally, areas with high population and traffic are chosen for measuring NO2. Since ozone is formed downwind from the sources, NO_2 levels downwind from the sources can also be high provided NO is also present in sufficient quantity.
CO	CO is emitted from vehicles and its measurement should be conducted near traffic intersections, highways, commercial areas with high traffic density. Generally, areas with high population density also have elevated vehicles counts and residential sources and these areas should also be considered for conducting CO measurements
O_3	Ozone is secondary pollutant and is formed in atmosphere by reactions of other pollutants such as NO, HC. Ozone precursors react to form ozone such that peak levels are observed at locations downwind of the sources. Thus, ozone stations should be located downwind from the sources. The inlet of the sampling probe of the ozone analyser should be positioned 3 to 15 meters above ground, at least 4 meters from large trees, and 120 meters from heavy automobile traffic and sampling probes should be designed to minimize O_3 destruction by surface reaction or by reaction with NO
Particulate Matter (Various size classes	The major sources of PM10 include dust originating from construction activities, re-suspension of dust from vehicles, tear and wear and residential / industrial sources. PM10 monitoring should be conducted where high levels of suspended particulate matter are expected. One of the major sources of PM2.5 are vehicles especially diesel vehicles, industrial processes such as combustion processes. PM2.5 monitoring should be conducted where high levels are expected.

Step 5- Identify Methodologies. Once the target pollutants have been identified a decision on the monitoring methodologies needs be mad, this could be a reference station using the higher cost and highly reliable equipment, or a decision could be made to utilise low cost sensors or passive sensors to determine whether a more rigorous monitoring is needed.

Step 6: establishment of the operation and management protocols: Station Operation and Management Protocols must be established as part of the AQ Monitoring Plan. The protocols must detail necessary standard operating procedures and work instructions to enable staff to effectively manage a monitoring network. this should detail:

- Roles and responsibilities for all personnel responsible
- Identify essential resource requirements for conducting air quality measurements such as manpower, infrastructure in the field and laboratory, equipment and finance.
- Include scheduling of station management, instrument maintenance and calibration for a sustainable operation of monitoring station.
- Provide data acquisition, management and reporting procedures.
- Identify sufficient financial resources to be made available for the operation of the stations, purchasing of new/replacement instruments, hiring of manpower, data management (processing, reporting, archiving) and undertaking laboratory quality assurance and quality control procedures.
- Include a plan to secure adequate resources (staff, equipment, spares, consumables etc.) to undertake the monitoring initiative.
- Present personnel capacity development plans of staffs involved in the operation, maintenance, calibration and reporting activities with the necessary training skill, expertise and qualification to undertake the work.

Step 7: Establish data management protocols: Data management protocols must be established as part of the AQ Monitoring Plan. These protocols must include QA/QC procedures for data management. Quality assurance of monitoring data is intimately linked to the entire air quality monitoring process, from the choice of site, choice of instrumentation, proficiency of staff, calibration and maintenance processes, data storage, and retrieval and analysis systems. The ambient air quality monitoring data will only ever be as good and reliable as the systems that produce it. Following the recommended format in the reporting of monitoring results is a step towards achieving national consistency in air quality reporting. The fundamental objectives of a quality assurance/control programme should be as follows.

- The data obtained from air quality measurement systems is representative of the spatial scale being investigated.
- A minimum data capture rate to be achieved, typically this is in the 70-80% range
- Define the minimum valid data is collected when calculating averages.
- Measurements are accurate, precise and traceable.
- Data is comparable and reproducible. Results from a monitoring network are internally consistent and comparable with national, international and other accepted standards.

Step 8: Data storage and reporting: Ambient air quality monitoring data storage and reporting protocols must be established as part of the AQ Monitoring Plan. These protocols must establish:

- Who data is to be reported to.
- How data is to be reported to different users and on which platforms
- How data is to be reported, e.g., exceedances, the Air Quality Index (AQI).
- How the public will have access to ambient air quality data.
- How data will be stored and archived for future generations.

Once the air quality monitoring plan has been established the type of sensors and the type of site needs to be determined. To start one should look at the types of sites that one needs to ensure there is representativity.

4.6.1.1 Reference Sites

The reference sites form the backbone of a comprehensive air quality monitoring network. it is in the reference sites that the primary observations are made. and these sites should be equipped with high quality instrumentation that has a low detection limit (within the expected range for the pollutant of concern) and a high precision and the instruments should meet national or international standards for the observations. the objectives for a Network of air quality reference stations s to ensure the correctness, representativeness consistency and accessibility of ambient air quality monitoring information.

- Correctness – air quality monitoring is of high quality, based on regulatory reference/equivalent methods for continuous monitoring; dust fallout standard reference methods and appropriate monitoring and analytical methods in passive sampling.
- Representativeness – relevant spatial/temporal variations and the extent of human exposure are considered when designing monitoring networks.
- Consistent – air quality data is recorded, analysed, processed, reported and archived consistently across all monitoring networks in the country following best-practice principles.
- Accessible – the public have access to ambient air quality information, and all users of air quality data have quick and easy access to methods, procedures and new developments in air quality monitoring and reporting.

The reference sites would typically include the following physical infrastructure

- Monitoring site enclosure: Ambient monitoring equipment must be housed in a shelter. The monitoring shelter's role is to provide security (robust and vandal-proof), electrical power and a temperature-controlled environment in which the sampling equipment can operate at optimum performance. The shelter must be corrosion free with a dry, leak-proof and stable environment. The shelter must be large enough to house a number of analysers on a sturdy rack for easy access for maintenance, and enough space to carry out routine calibration and basic repairs to the equipment onsite. A constant temperature is important as most analysers are temperature sensitive, with moderate variations in temperature affecting data. An air-conditioning unit with heat and cool cycles is required to prevent variations in temperature. The mean shelter temperature must be controlled at 25°C ± 5°C. Internal temperatures within the monitoring shelter must be recorded and stored and supplied with the data. Should the temperature rise to above/below this range, the data must be flagged for possible erroneous results in the database. Where possible, a dual air-conditioner system should be considered. The two air-conditioners should be programmed to be used alternatively to ease the strain on one air-conditioner. Appropriate air driers need to be used in humid environment such as coastal sites as any water condensation in any analyser may render the data invalid.
- Sampling inlets and manifold: Sampling probes should be of Teflon, glass or stainless steel with Teflon connections. It must be laminar flow in design, typically 30-50 mm in diameter. The air sample should be drawn through the system using a reliable fan or pump. This line must be chemically inert. The sampling line must maintain laminar flow. Its residence time should be as short as practical, and this resident time must be checked and documented. A filter must be installed at the inlet of the sampling line leading to the instrument to prevent contamination of the sampling component by ambient particulate matter. The probe must be cleaned monthly and sampling lines inspected for soiling. PM Sampling should have its own inlets.
- Data Logging Systems: the reference stations should have appropriate data logging systems, these access data from a variety of sensors, perform programmed calculations including conversion between units of measurements, store the data in memory and can be used for transmitting the data to external servers for archiving and analysis.
- Data Connectivity: for the transmission of data from the instruments and their data loggers to remote and centralized servers, this should be in place and of a magnitude that can handle the volume of data transmission
- Calibration systems; to ensure the accuracy and traceability of the data reference station networks would need calibration systems, these typically include certified calibration gases that are traceable to national and/or international standards (the National Metrology institute may produce these reference gases or a reference material from an international accredited laboratory may be required) and that have a certified calibration certificate and an estimated uncertainty of the measurement, typically a reference network would include a certified zero gas and calibration standards for each of the species monitored at an appropriate concentration. In addition, it is useful for networks to utilise dilution calibrators with calibrated mass flow controllers that can accurately and with flow traceability provide dilutions while performing multipoint gas calibrations.

4.6.1.2 Reference methods

With the focus of the pollutants of interest for the reference air quality monitoring network decided the appropriate monitoring methodologies need to be utilised to ensure standardisation and quality of the measurements. A number of approved methods that might be appropriate, these include:

- United States Environmental Protection Agency (US EPA)
- European Standards (EN)
- Technischer Überwachungs-Verein (TÜV)

- United Kingdom Environment Agency's Monitoring Certification Scheme (MCERTS)
- Australia Environmental Protection Agency (AEPA)
- National Metrology Institute of South Africa (NMISA)

While it is beyond the scope of this report to standardise on a certification standard, cognizance needs to be taken to ensure that the equipment procured meets the standards of a reputable standardization body.

4.6.1.3 Low-Cost Sensors

While low-cost sensors (LCS) cannot replace reference-grade monitors for long-term health impact assessments, several platforms have integrated data from low-cost sensors with data from official reference-grade monitors to provide global overviews of real-time air pollution. This can help raise awareness and inform public action. One such platform is OpenAQ (https://openaq.org/), a non-profit open-source database that provides near real-time data on PM, CO, SO_2, O_3, NO_2, VOCs, and other meteorological parameters. OpenAQ combines data from both reference-grade monitors and low-cost sensors to gather air quality data globally. Included networks come from agencies such as the US EPA AirNow, Environmental Defence Fund, Carnegie Mellon University, and Clarity Movement.

Low-cost sensors can be grouped into different categories based on the operating principles of these devices: resistive or metal oxide sensors, electrochemical or amperometric sensors, non-dispersive infrared radiation absorption (NDIR) sensors, photoionization detectors, and optical particle counters (OPC), which measure light scattered by individual particles (Amegah et al. 2021; Yatkin et al. 2022; Lewis, von Schneidemesser, Erika, and Peltier, Richard J. 2018; Bainomugisha, Ssematimba, and Okure 2023).

Low-cost sensors, particularly those capable of measuring multiple pollutants, have the potential to provide real-time, highly localized data. This capability can help fill monitoring gaps in regions with limited or no atmospheric monitoring infrastructure. When deployed in large, spatially distributed networks, these sensors can enhance the detection of local emission sources, assist in validating model-reconstructed fields or satellite data both qualitatively and quantitatively, and support assimilation techniques, especially in areas that are under-monitored.

Currently, there are several global LCS networks. PurpleAir sensors form a vast global network of more than 10,000 sensors. However, this network has often shown deficiencies in measurement accuracy, with some corrections proposed to improve the accuracy of the products across multiple regions, making it reliable enough to communicate the air quality index (AQI) and support public health messaging (Barkjohn et al., 2021; Collier-Oxandale et al., 2022).

Clarity Movement (https://www.clarity.io/) is a company that designs and deploys low-cost sensors for air quality monitoring. Its aim is to provide accessible, real-time data on pollutants such as PM2.5, PM10, NO_2, and O_3, using optical sensor technology. Over 10,000 devices have been deployed in more than 85 countries to improve air pollution monitoring.

Another low-cost monitoring network with special importance in Africa is AirQo (https://www.airqo.net/) (Bainomugisha, Ssematimba, and Okure 2023). AirQo is a project developed by Makerere University in

Uganda focused on air quality monitoring to improve air quality in African cities. This network uses low-cost sensors designed and built in Uganda, specifically adapted to local conditions. Over 500 hundred stations are deployed in Africa, primarily in Uganda, to measure mainly PM2.5 and PM10, with some sensors also measuring gases like NO_2 and CO.

4.6.1.4 Atmospheric Deposition

The DEBITS (Deposition of Biogeochemically Important Trace Species) and INDAAF (International Network to Study Deposition and Atmospheric Chemistry in Africa) networks play a crucial role in understanding atmospheric deposition across Africa (Galy-Lacaux and Delon 2014; Conradie et al. 2016b; Vet et al. 2014). DEBITS was established in 1990 under the IGAC/IGBP program to assess wet and dry atmospheric deposition in tropical regions, while INDAAF, launched in 1995, focuses on long-term monitoring in Africa. These networks operate multiple sites across key ecosystems—dry savannas, wet savannas, and equatorial forests—monitoring the deposition of nitrogen (NOx, NH_3) and sulphur compounds . Their work helps quantify emissions from sources like biomass burning, agriculture, and fossil fuel combustion, providing critical data for evaluating air pollution's environmental and climatic effects.

Atmospheric deposition in Africa is influenced by both natural and anthropogenic sources, with nitrogen and sulphur compounds significantly impacting air quality and ecosystems. Studies conducted under INDAAF reveal spatial and seasonal variations in ammonia (NH3) and nitrogen oxide (NOx) concentrations, driven by factors such as biomass combustion, agricultural activities, and meteorological conditions. Measurements indicate that wet and dry deposition processes vary across ecosystems, with forests exhibiting higher nitrogen deposition rates than savannas. The networks also highlight the role of atmospheric deposition in soil acidification and nutrient cycling, emphasizing the need for long-term monitoring to assess environmental changes and inform mitigation strategies

The methodology that should be deployed is that of the Deposition of Biogeochemical Important Trace Species (DEBITS) program of the International Global Atmospheric Chemistry (IGAC) and the Global Atmospheric Watch Program of the World Meteorological Organisation (WMO) (Conradie et al. 2016a) and using the WMO field protocols for Precipitation Chemistry (WMO/GAW 2004), as this as this ensures continuity with existing observations on the continent.

Analysis of the samples will be conducted at a laboratory that has participated in the GAW DEBITS intercomparison program to ensure intercomparability with the international observations. The Following Parameters will be measured on each sample.

a. Rainwater pH
b. Conductivity
c. Analysis for the inorganic cations and anions. The following parameters will be measured :
    i. Sodium (Na^+)

ii. Ammonium (NH_4^+)
iii. Potassium (K^+)
iv. Calcium (Ca_2^+)
v. Magnesium (Mg^{2+})
vi. Nitrate (NO_3^-)
vii. Chloride (CL^-)
viii. SulphateSO_4^{2-})

d. Analysis of the following water-soluble organic acids:
i. Formic acid (COO^-)
ii. Acetic acid (CH_3COO^-)
iii. Propanoic acid$C_2H_5COO^-$)
iv. Oxalic acid ($C_2O_4^-$)

As an addition to the wet deposition analyses the use of passive sampling may be considered . Passive samplers will be used for the measurement of ambient concentrations of NO_2, SO_2, Ozone, NH_3, and Nitric Acid (HNO_3). This methodology follows that of the IGAC DEBITS Africa (IDAF) network (Adon et al. 2010a; Josipovic et al. 2010; 2011) with ion chromatography to calculate the net flux of each gas.

And to analyse the composition of the aerosol component, the aerosol chemical composition can be determined using two particle samplers (such as the Minivol) with a 10µm or 2.5µm impactor collecting to a quartz and a Teflon filter. The samplers will be operated for a single 24-hour period per week. The samples collected on the Teflon filter will be analysed for inorganic compounds, while the quartz sampler will be analysed for the organic compounds. Following the sampling the filter will be weighed to get a gravimetric mass sample and the flow volume will be recorded to determine the total flow. This is also per the DEBITS methodologies (Conradie et al. 2016a; Adon et al. 2010b).

4.6.1.5 Radiation measurements

Radiation measurements play a critical role in atmospheric monitoring, as they provide key insights into energy transfer processes between the Earth's surface, atmosphere, and space and have a variety of applications in climate models and weather forecasting:

- Photosynthetically Active Radiation (PAR) is a key variable used to study plant productivity and carbon uptake
- Radiation measurements help quantify the earth's energy balance/budget by measuring incoming solar radiation, reflected radiation, and outgoing longwave radiation
- Albedo measurements are key for understanding surface heating/cooling patterns, and are a key parameter to obtain to understand the impacts of land use and land cover change
- Radiation attenuation measurements are used to estimate aerosol concentrations and cloud radiative effects

- UV radiation measurements help assess the concentration of ozone and other pollutants that absorb or scatter radiation (air quality monitoring)

Improving the spatial spread of radiation measurements would greatly improve our understanding of attributing atmospheric variability between aerosols, clouds, and water vapor. Additionally, a continental RI standard for regular calibration would maintain radiation measurement accuracy. -

4.7 Support Infrastructure

The Atmospheric observations to function require an extensive network of support infrastructure, this includes technicians, metrological services, instrumentation support and data support

4.7.1 Technician services

The continued and long-term operation of this network of observations, a cohort of skilled technicians is required. Their role is the installation of the equipment, undertaking routine and non-routine instrumentation checks and services including scheduled instrumentation maintenance and the basic repairs, the performance of calibrations and basic oversight of the data. The technician cohort requires skills related to analytical chemistry, instrumentation and metrology or some of the engineering professions. Experience indicates that the technician cohort can be drawn from the natural sciences (especially the physics and chemistry, meteorology and climatology) or the engineering professions.

4.7.2 Meteorological Services

To maintain a network of atmospheric measurements it is necessary that there is sufficient capacity in metrological services to provide traceability of the measurements. This includes at a minimum gas metrology to traceability for the gas observations that are traceable to the SI system and to international measurements. A number of the countries in Africa have some capacity in this regard and it must be developed and encouraged. This includes traceability for greenhouse gases such as CO_2, CH_4 and N_2O. In addition, traceability for O_3 is a priority as are the criteria pollutants (SO_2, NO_2 and CO).

Associated with this it is necessary to maintain traceability of the primary meteorological variables, including temperature, pressure and humidity. Finally, the traceability for radiation sensors.

In the South African context this traceability is maintained by the South African Metrology Institute which commercially provides reference materials and calibration services.

4.7.3 Instrument Suppliers

Thirdly it is necessary to have a network of instrument suppliers who can provide and service the instrumentation that is required and that can engage with the OEM for complex repairs. The local suppliers should be trained and supported by the OEM and this is something that should be confirmed during the procurement process.

4.8 Primary digital data

This speaks to all the variables that need to be measured in the instrumentation stations. Linking into the needs identified in the WMO Oscar and the GCOS essential climate variables and the expanded set of variables summarized by Ballasteros et al 2018 (Lopez-Ballesteros et al. 2018) An approach for the network should be to maximize the number of the essential Atmospheric variables measured.

It seems likely that any continental network will consist of a network of a high precision sites focusing on atmospheric composition such as greenhouse gases, ozone, precursors of ozone and aerosols and criteria pollutants and wider network of lower cost sensors that expand the number of observations and improve the spatial representativity across the continent. It should prioritize those columnar variables that includes GHG, aerosols and ozone as well as radiation, meteorology parameters (wind speed and direction, pressure, temperature), relative humidity, rainfall.

Similar to the Cape Point atmospheric station, the parameters that could be prioritized include GHGs, other trace gasses, halocarbons, aerosol optical properties and AOD, solar radiation, meteorology parameters (wind speed and direction, pressure, temperature), relative humidity, rainfall. Different instruments such as flask sampling, NaOH sorption flask etc. can be used to measure the above-mentioned variables (Dvorska et al 2015). Need to confirm the exact instruments for each variable.

4.8.1 Secondary digital data

Secondary data is crucial as it helps the RI to tie its primary data context. In-situ data will improve satellite estimates, which in turn can be used for larger scale (spatial and temporal) data coverage. Moreover, the secondary digital data could be the topography, climate, land cover or land use and geology information of the site.

4.8.2 Digital infrastructures

Each theme of the atmospheric composition RI should have a digital infrastructure that is suitable for its data type. The infrastructure should consist of the tool that will first archive, then analyse the raw incoming data until it is in a format suitable for sharing, this would include some preliminary processing and cleaning and the removal of spikes, offsets and drifts in the data. The data should be stored in a minimum of three levels including; the raw data from the instruments, the initial cleaned data which should be through an automated cleaning process, and finally a cleaned, corrected and if necessary, gap filled dataset. The digital infrastructure should be managed by one organization agreed on by the consortium.

4.8.3 Data management, analysis and modelling

The RI should have a data management portal that offers services for visualization and analysis of data. The data infrastructure should be an open data platform allowing all the relevant stakeholders to access and use the data. For convenience the processed data should be grouped according to the RI themes. There should be a standardized way of handling data across all the atmospheric composition stations. The proposed RI can adopt the GAW data management structure. GAW has four central facilities; quality assurance or science activities centres (QA/SAC), world calibration centres, central calibration laboratories (CCL) and world data centres (WDC). These centres are crucial because for example the GAW CCLs is important for a network-wide comparability of measurement data and WCCs for improving the data quality in various ways. The diagram below shows a possible standardized way of handling data.

4.8.4 Modelling and Remote sensing

The RI should make use of relevant model output for areas where true observations are scarce. Models should be used to produce data that covers a large area, especially because in-situ observations are generally point observations. In-situ measurements should be used to verify the model data. In-situ data should have the capacity to verify the climate models and should be planned to operate over the long term. Similarly, the combined use of in-situ observations and remote sensing products should be used to cater to the strengths of each of the observation methods. The remote sensing could close the spatial scales that are unreachable through in-situ observation, however the in-situ observations allow for the verification and improvement of the RS algorithms.

4.8.4.1 Data storage or repositories

Copies of all data products handled by the data management should be stored in a safe, long-term manner in the infrastructure repository. The data stored should always follow the FAIR principle; Findable, Accessible, Interoperable and Reusable. All the datasets archived or published should always be accompanied by the metadata. Data infrastructure should sufficient storage for archiving the data emanating modelling and remote sensing outputs, this may be very large depending on the modelling domain .

4.8.4.2 Data sharing and reuse

To successfully manage the data, the RI should have a license in place that users will have to agree to its terms and conditions, appropriate licenses would be the creative commons with attribution, or an equivalent License . The license should allow the users to share and adapt the data under certain terms and conditions. The terms and conditions of the license should emphasize the use of proper reference and citation of the data. Users should also inform the providers when they have used the data for publication.

4.8.5 Knowledge management and skills building

4.8.5.1 Knowledge exchange

RI products should be showcased in different platforms such as conferences, interviews etc. Knowledge can also be shared via publishing research papers, policy briefs etc.

RI should have outreach programs that involve school and community visits to educate people about the RI and share its outputs.

4.8.5.2 Knowledge preservation

There should be efforts in place to safeguard and maintain the RI output/s. Those efforts will ensure long-term accessibility of data. Data portals should be regularly maintained and upgraded to avoid loss of data and archived for long term storage, and where possible data should be shared on global platforms

4.8.6 Skill development or capacity building

Everyone that is responsible for operating the RI should be trained, that would improve the quality of data as less mistakes will be expected to occur. Data curators should also get training on how to manage the data. This means there should be regular training as equipment and technology are known to change with time. Users should also be trained on how to access and use the data.

4.8.6.1 Scientific Capacity

The expertise and knowledge base for researchers and academics to use the RI effectively include training in interdisciplinary fields such as biogeochemistry, ecology, climate and atmospheric sciences as well as appropriate statistical, computational and modelling skills for handling and analysing large data sets. A comprehensive approach that incorporates multidisciplinary education, specific training programs, and improved data science abilities is needed to build scientific capacity for researchers to use RI in interdisciplinary fields. This includes providing training in statistical analysis, and big data management in addition to training in biogeochemistry, ecology, and data analytics through modular workshops, online courses, and certificates. While promoting collaborative research networks through cross-institutional projects and conferences fosters information sharing, joint degrees, research fellowships, and internships can develop multidisciplinary expertise. Researchers are also guaranteed to be prepared to use RIs efficiently if they invest in practical RI training, provide thorough guides, and receive soft skills training in project management and communication

4.8.6.2 Stakeholder actors and community engagement

This section is similar to the co-concept section. There should be stakeholder engagements such as conducting workshops, interviews, one-on-one where the outcomes of the RI will be shared. These engagements could improve the knowledge of the stakeholders.

4.8.6.3 Feedback mechanisms

Stakeholders should be given a platform to comment, suggest, and evaluate the RI. There should then be a systematic way (whether it’s interviews, workshops, surveys etc.) of responding to their comments and suggestions. This will ascertain stakeholders that their voices are heard and taken into consideration and thus promoting trust and long-lasting relationships.

4.8.7 Dissemination and accessibility

The RI outputs should be disseminated in various ways available. For example, publication of research papers. Publication of reports, policy briefs, newsletters and social media posts. The use of local languages should be promoted especially in the local newsletters. This will enable the outcomes to reach all the relevant stakeholders.

4.9 Governance and compliance

4.9.1 Standards, policies and ethical consideration

There should be a set of principles, guidelines and practices that govern the planning, development, operation and dissemination of RI activities, with good ethical practices. In the stages where, human engagement is required especially the community members, ethical clearance should be obtained. The outputs should meet the government standards for each activity, including the collection of the data and the dissemination of that data.

5 Research infrastructure with a biodiversity focus

This section outlines a draft concept for a pan-African Biodiversity-focused Research Infrastructure (RI). Since KADI aims to provide concepts for developing the best available science and science-based services for Africa, the biodiversity-focused RI will be implemented to improve a common global action to combat climate change and its impacts through biodiversity. Globally a number of RIs have been established to improve the understanding of biodiversity, functioning, and management of ecosystems, and how these ecosystems respond to environmental changes such as climate variability, extreme weather events, altered fire regimes, and changing land use types (Karan et al., 2016). Biodiversity-focused RIs should provide a holistic and comprehensive understanding of the role of biodiversity in land cover change, ecosystem structure, -function, and -management. Important questions to consider when developing a biodiversity-focused RI include:

- How can biodiversity be used to combat climate change and its impacts?
- What biodiversity observations or measurements are needed to better understand climate change and its impacts?
- In the long term, what essential biodiversity variables (EBVs), for example genetic composition, species populations, species traits, and community composition, need to be measured and monitored to enhance our understanding of the essential climate variables (ECVs) such as ecosystem structure, -function, and land cover change?

‘Biological diversity is the key to the maintenance of the world as we know it.’ – Edward O. Wilson

Biodiversity is a multi-faceted, scale-dependent property in space and time (Townsend et al., 2003). It can broadly be defined as the variety and variability of living organisms at different levels and ecological systems in which they live (Begon, Harper, and Townsend 1990) (Rawls, 2004). Biodiversity provides the foundation for ecosystem services such as nutrient cycling, climate regulation, food production, and regulation of the water cycle, and is therefore strongly linked with human well-being (Pereira et al., 2012). Biodiversity exists at various levels of complexity, and includes genetic-, species-, functional (traits)-, community composition-, and ecosystem diversity (GEO BON, 2024.). Data on one or more of these dimensions over time and space support biodiversity assessments in marine, terrestrial, and freshwater ecosystems. Information on how biodiversity changes in these environments is necessary for policymaking. Additionally, given that biodiversity is a necessary driver of ecosystem stability, function, and sustainability in the face of environmental changes (Loreau 2010), understanding and maintaining all facets and fluxes of biodiversity should be a key focus for managing authorities. Reducing the rate of biodiversity loss, and preventing drastic changes in biodiversity are international goals of parties to the United Nations (UN) Convention on Biological Diversity (CBD) (Pereira et al. 2013). However, there is no global, standardised observation system that delivers regular, timely data on biodiversity change (Pereira et al. 2013), reasserting the importance of biodiversity-focused RIs. These RIs can be used to detect change in essential climate variables (e.g. land cover, ecosystem function and -structure) by collecting systematic biodiversity observations using standard formats, protocols, and methods, together with environmental monitoring of essential biodiversity variables (EBVs). These observational data can be moved and shared to open databases. Ensuring that data are interoperable across databases will make efficient use of biodiversity information for guiding conservation and sustainable development strategies (Pereira et al. 2013; GEO BON, n.d.).

Plant communities form the structural and functional basis for most terrestrial ecosystems, therefore, an improved understanding of community ecology (e.g. species co-occurrence across spatial and temporal scales (McGill et al., 2006)) is necessary for the enhanced conservation of biodiversity (Pärtel et al., 2017). There are a number of observatories across the globe and Sub-Saharan Africa gathering data and conducting analyses on the structure and function of vegetation. One such observatory is the Socio-Ecological Observatory for Studying African Woodlands, or SEOSAW (Ryan, CM 2021), which comprises a network of scientists, and woodland and savanna survey plots across Sub-Saharan Africa (Figure 16).

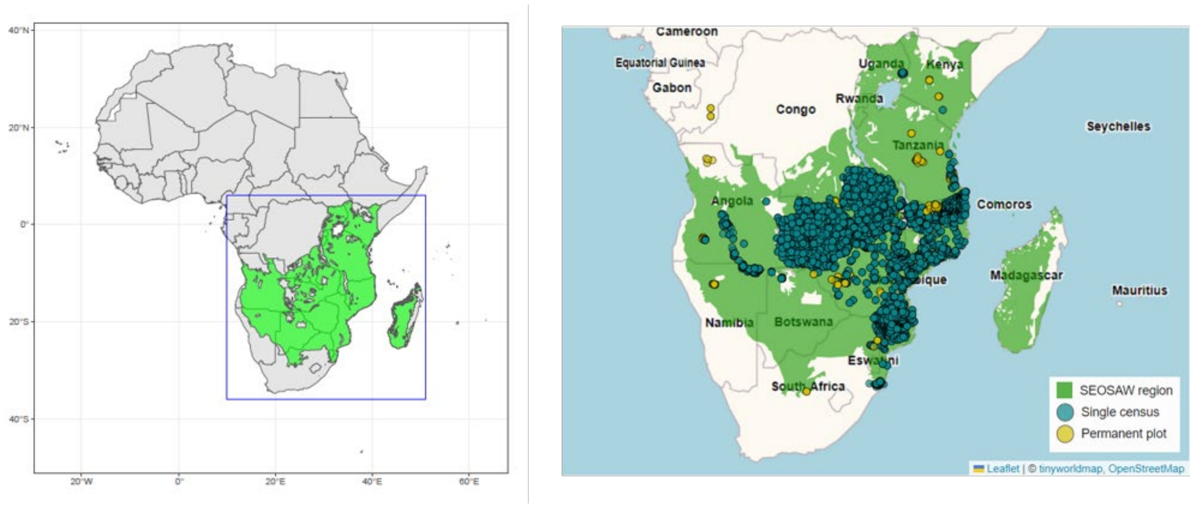

Figure 16 Map of single census (blue) and permanent (yellow) SEOSAW plots across Africa. (https://seosaw.github.io/index.html).

ForestPlots.net (https://forestplots.net/) is another observatory that provides a unique platform for everyone to measure, monitor, and understand the world's forests, especially tropical forests. Individual trees are measured in hundreds of locations across Africa, using standardised techniques allowing the behaviour of tropical forests to be measured, monitored, and understood. (Figure 17).

Figure 17 Map of single census (yellow) and multiple census (red) ForestPlots.net plots across Africa

The African Tropical Rainforest Observation Network (AfriTRON), is another example of an international network of researchers engaged in on-the-ground long-term monitoring of tropical forests (Figure 18).

Figure 18 Map of single census (yellow) and multiple census (red) AfriTRON plots across Africa (https://afritron.org/)

5.1 Foundation characteristics

5.1.1 Theory of change

The Biodiversity-focused research infrastructure should promote and improve a holistic and comprehensive understanding, description, and illustration of biodiversity's role in the functioning and management of ecosystems. The aim is therefore to enhance our understanding of ecosystem response to environmental changes, such as climate variability, extreme weather events, altered fire regimes, and changing land use types in the context of biodiversity (Karan *et al*., 2016). Long-term biodiversity data is essential for such variables to be better understood. These long-term data can be used to comprehend temporal and spatial changes in biodiversity to help with the development of attainable ecological management plans, and climate services. The Biodiversity RI should therefore enable society to better manage the risks and opportunities arising from climate variability and change. To be able to provide a holistic and comprehensive understanding of biodiversity's role in the functioning and management of ecosystems in the face of climate change, Biodiversity-focused RIs should strive to follow a global framework for long-term biodiversity monitoring. Similar to the Climate Services Framework (https://nccis.environment.gov.za/climate-services), such a framework might be built on the following five pillars. 1) Biodiversity Observations and Monitoring - this pillar helps ensure that the biodiversity observations necessary to meet the needs of end-users are met and managed, supported by the relevant metadata, 2) Platform User Interface - the Platform User Interface pillar provides a structured way for users, biodiversity researchers, and biodiversity data and information providers to interact at various levels, 3) Biodiversity Service Information System - the principal mechanism through which biodiversity information (past, present, and future) is routinely collected in a standardised manner, stored, and processed to generate products and services which inform decision-making processes, 4) Biodiversity Research, Modelling, and Prediction - this pillar supports the development of tools and methods to facilitate the transition of research to operational biodiversity service provision (i.e. the provision and use of biodiversity data, information, and knowledge to assist decision-making), and produce practical implications of biodiversity information, 5) Capacity Development - the capacity building pillar will strive to develop and enhance existing capabilities which are needed to enable management of biodiversity risks effectively.

5.1.2 Products, solutions, and outputs

The proposed Biodiversity-focused RI should produce various outputs and products to all interested stakeholders and parties. These outputs and products should be provided in different forms, for example, publications by researchers in peer-reviewed journals using biodiversity data provided by the RI, including; publications, booklets, newsletters, and strategies that can be repeated and applied by other organisations and institutions. Data from the observation networks should enable researchers to develop and answer research questions, and communicate those findings through research papers, conference presentations, and workshops. Outputs from the RI should, furthermore, enable the government to make informed decisions with respect to biodiversity in Africa. These decisions can be

communicated via direct policy input, research publications or the provision of facilities for conducting targeted research into specific areas of concern.
Other forms of outputs that the RI should aim to provide include the development of open-access data platforms, systems, and tools, reliable long-term observational data (e.g. vegetation information and maps, land use changes and maps), and data supply and sharing.

5.1.3 Impact pathways

When linking the RI's inputs, actions, activities, outputs, and outcomes to reach the desired impact, the following factors should be considered:

5.1.3.1 Co-design

The relevant and interested stakeholders should be involved in the planning and design of the infrastructure. This entails:

- Planning where the network of research infrastructure should be deployed and developed. This should consider the spatial and biome coverage at the national and continental scale, and should capture significant gradients such as aridity, latitude, altitude, rainfall, and land use,
- What the key variables to be measured are, as a starting point this should be the listed variables from the Group on Earth Observations Biodiversity Observation Network (GEO BON) for Essential Biodiversity Variables (EBVs),
- Who is going to finance the RI? When considering the financial aspects important things to consider include whether it is going to be funded by all the interested organizations or only one organization, and what are the benefits for both options
- Technical maintenance – who is going to be responsible for this, and how all the involved parties are going to benefit at the end.

Co-design minimises the chances of missing crucial components of the RI, whilst promoting trust and transparency between all parties involved.

5.1.3.2 Ground- based measurements and measurement traceability.

A biodiversity-focused RI should capture the various classes of EBVs including Genetic Composition, Species Populations, Species Traits, Community Composition, Ecosystem Functioning and Ecosystem Structure (GEO BON, n.d.). The RI should include both aquatic and terrestrial biodiversity monitoring stations and protocols. Mention the aquatic and terrestrial instrumentation and observation methods. Data from terrestrial and oceanic domains are mainly taken from techniques based on in situ and/or remote sensing observations, and inventory/census (López-Ballesteros et al., 2019).

5.1.3.3 Data archiving and analysis

Biodiversity data should be managed using standardised databases and analysed with appropriate tools for each level of biological organisation. Here are common tools used for different aspects of biodiversity analysis (https://www.pangaea.de/).

1. **Genetic Composition**
   - **Tools**: BLAST (Basic Local Alignment Search Tool), MEGA (Molecular Evolutionary Genetics Analysis, https://www.megasoftware.net/), BEAST (Bayesian Evolutionary Analysis Sampling Trees, https://beast.community/), Geneious (https://www.geneious.com/), TASSEL (Trait Analysis by Association, Evolution, and Linkage), PLINK
   - **Dataasi**: GenBank, EMBL-EBI, Dryad, Ensembl, Barcode of Life Data System (BOLD)
2. **Species Populations**
   - **Tools**: R (packages like 'popbio', 'vegan'), MARK, DISTANCE, Presence
   - **Databases**: Global Biodiversity Information Facility (GBIF), IUCN Red List, OBIS (for marine species), Map of Life (https://mol.org/), Mammal Diversity Database (MDD, https://www.mammaldiversity.org/
3. **Species Traits**
   - **Tools**: Trait-based analysis in R (e.g., 'FD' package), BIEN, TraitEx
   - **Databases**: TRY Plant Trait Database, FishBase, BirdLife International, PanTHERIA,
4. **Community Composition**
   - **Tools**: R (packages like 'vegan', 'phyloseq'), PRIMER-E, Canoco
   - **Databases**: GBIF, BIEN, iNaturalist, eBird
5. **Ecosystem Functioning**
   - **Tools**: Ecosystem modeling tools like InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs, https://naturalcapitalproject.stanford.edu/software/invest), SELES (Spatially Explicit Landscape Event Simulator), R (packages like 'deSolve', 'EcoSimR')
   - **Databases**: FLUXNET (https://fluxnet.org/), DataONE (https://www.dataone.org/), LTER (Long-Term Ecological Research)
6. **Ecosystem Structure**
   - **Tools**: Google Earth Engine, LiDAR, ArcGIS, QGIS
   - **Databases**: NASA Earthdata, Copernicus, Global Forest Watch

5.1.3.4 Validation

The produced data should be validated using the appropriate remote sensing data and stakeholder engagements. For example, in addition to ground-based measurements, what remote sensing technique (s) could be used to estimate the diversity of the specific plant or animal species in a specific region.

5.1.3.5 Dissemination of information

The biodiversity RI should ensure that data is open-access in the data portal of the managing organization. Means of accessing the information according to the FAIR Principals should be implemented. Information should be disseminated in all applicable ways (i.e. research papers, conferences, workshops, newsletters, and booklets).

5.1.3.6 Training on usage of data

If the RI is managed by a consortium of different organizations, each organization should make it their responsibility to train the data users on data usage. Inadequate knowledge on how to use the data may result in the misuse and misinterpretation of the data. There should be a standard data usage course across all the organizations that will be conducted regularly.

5.1.3.7 Actions taken based on the knowledge from RI

As the RI intends to overcome certain issues, knowledge generated from it should be incorporated to resolve some, if not all the issues that were of concern during the planning of the RI. Actions should be taken based on the obtained knowledge. For instance, based on the knowledge regarding species composition or diversity in different regions, suitable mitigation measures combating negative threats to species can be implemented.

5.1.4 Monitoring, Evaluation and Learning of Impacts

Impacts of the RI should be regularly monitored. This involves meetings between stakeholders to revise what was said to be the goal of the RI. The stakeholders should use a set of indicators to evaluate the goal or objective of the RI. Participatory Monitoring Evaluation Reflection Learning (PMERL) is a tool that is often used to monitor the activities. This tool can be adopted to monitor the impact of a RI. The tool is self-explanatory, meaning after stakeholders have participated in the development of the RI they should be involved in all the following steps which are monitoring, evaluation, reflection and learning. PMERL gives an opportunity to improve the performance of the RI.

5.1.5 Co-concepts

In every step of establishing the RI, co-design, creation, production is critical. All the relevant or interested stakeholders should be involved in every step; from planning of the RI to finally disseminating the product or output. There should be clear understanding who is involved in which stage. It should also be taken into consideration that some stakeholders will join at the later stages.

5.2 Observations, data sources, and technologies

5.2.1 Observations, measurements, and monitoring

This links to the first pillar as discussed under the 'Foundation Characteristics' section. An important step in developing a Biodiversity-focused RI is to ensure that the biodiversity observations necessary to meet the needs of end-users are met and managed, supported by the relevant data. Therefore, site identification and selection for RI in support of biodiversity research, needs to be performed carefully. A review process, or auditing of existing RIs should be performed, to obtain the spatial distribution of the existing networks. New research infrastructure, observations, and monitoring should then be established where gaps are identified. The exact location of the proposed RI should be determined by practical considerations, such as topography, presence of existing infrastructure, and relevant biodiversity-related research questions. This information can additionally be used to identify, and delineate reference sites to enable proper biodiversity restoration activities. The co-location with other RIs, such as carbon exchange observation, and atmospheric composition RIs, should be prioritised and fostered. This would promote collaboration between the RIs, and create linkages between the various ecosystem drivers and responses. Outputs from the respective RIs can then potentially be combined to determine possible linkages between them.

Instruments and observations capturing different biodiversity focal areas, themes, and Essential Biodiversity Variables (EBVs), can be deployed in various sites, and, depending on the needs of researchers in each particular location, appropriate standardised methodologies can be applied. Biodiversity RI should ideally be distributed across African countries to capture the variation in biodiversity of the continent, including a range of biomes, vegetation types, land uses, and gradients of environmental change and their drivers. Regions facing threats to biodiversity should be prioritised. Although important to include such a wide range of landscapes, it is vital to consider that various landscapes will occur in different biomes, and vegetation types, and they could have different environmental drivers, for example fire, herbivory, frost, rainfall, geology, and water availability. Drivers occurring in one landscape, could potentially not necessarily occur in another.

Because biodiversity is complex, multi-faceted, and scale-dependent, the concept of EBVs was introduced to advance the collection, sharing, and use of biodiversity information (Pereira et al., 2013; Navarro et al., 2017). EBVs can be used to identify indicators for biodiversity that reflect responses to change. Similarly, Essential Climate Variables (ECVs) are physical, chemical, or biological variables or a group of linked variables that critically contribute to the characterisation of the Earth's climate (https://gcos.wmo.int/en/essential-climate-variables/about). Long-term patterns in the dynamics of various functional groups (i.e. woody and herbaceous plants, large mammals, small vertebrates, terrestrial invertebrates, aquatic vertebrates and invertebrates, soil microbes and sediments (Figure x)), could provide a lot of information and insight into important ecological processes, and changes in climate and environmental drivers, leading to improved management of ecosystems and natural resources.

Given that plant communities form the structural and functional basis for most terrestrial ecosystems, vegetation dynamics are vital to observe, and often form the focal areas for international observatories such as SEOSAW, ForestPlots.net, and AfriTRON. Through such observatories that collect data on species diversity, species abundance, phenology, biomass, productivity, and utilisation, a lot can be deduced about aquatic and terrestrial ecosystem structure, -function, community composition, species populations, species traits, and genetic composition. Figure 19 presents a metric of the potential groups to observe and the properties to sample in a biodiversity focused RI. As a matter of prime importance for the climate services needs and for linkages to the biogeochemical and modelling processes the vegetation groups should take priority, and observations of the other taxonomic groups being conducted in the established sites when and where possible. This may be done within the RI, or

Properties	Woody Plants	Grasses and Forbs	Large Mammals	Small vertebrates including small mammals herpetofauna and avifauna	Terrestrial Invertebrates	Aquatic Vertebrates	Aquatic Invertebrates	Soil Microbes	Sediments
Diversity	✓	✓	✓	✓	✓	✓	✓		
Abundance	✓	✓	✓	✓	✓				
Phenology	✓	✓							
Biogeochemistry	✓	✓							
Biomass and Productivity	✓	✓	✓						
Metagenomics								✓	✓

Figure 19 Biodiversity sampling scheme showing the functional type and the properties to be sampled

This data can be used to produce outputs and tools such as vegetation and land use maps. Ground truthing, and long-term monitoring should be done continuously, so that changes can be detected, captured, and illustrated.

There are various major types of biodiversity data that can be collected (according to the Swedish Biodiversity Data Infrastructure - https://biodiversitydata.se/share/our-data/data-types/) including metadata only (data describing a dataset), checklists (a list of species or higher taxa), occurrence data (provides information about the location of an individual organism in time and space), sampling-event data (data collected using standard protocols for measuring and monitoring biodiversity), remote sensing (RADAR and LiDAR) (remote sensing for biodiversity can be used for habitat mapping including species area curve and habitat heterogeneity, species mapping/distribution, plant functional diversity/traits, spectral diversity including vegetation indices and spectral species).

5.2.2 Technician services

For the continued long-term operation of a Biodiversity-focused RI, a variety of resources is needed, including a cohort of skilled technicians with specific skill sets and training, in-field requirements (i.e.

vehicles able to drive in the different landscapes, access to the sites, collection permits), herbaria and identification services, sufficient and appropriate storage for samples.

5.2.3 Primary digital data

This refers to all the essential biodiversity variables that need to be measured by the observation stations. According to Lopez-Ballesteros *et al* (2018) the variables that could be prioritized include species genetic composition, species populations, species traits, and community composition (GEO BON, n.d.; Pereira et al., 2013). Some methods for measuring these essential variables include genotypic selection and metagenomics, presence and multi taxa surveys, or remote sensing (e.g., for detecting annual changes in leaves or studying biomass cover).

5.2.4 Secondary digital data

Secondary data is crucial, as it helps the RI to tie its primary data context. In this context the secondary data may be the primary data from other observation RIs and may include the suite of information such as Climate data, atmospheric composition, soils, hydrology and the socioecological aspects including land use and land management. Secondary data could be the remote sensing data and could be validated by the *in-situ* data. Additionally, topography, climate, land cover or land use and geology information are useful data that can be used to tie with the primary collected data.

5.2.5 Digital infrastructures

Each theme of biodiversity RI should have a digital infrastructure suitable for the respective data type. The infrastructure should consist of the tools to analyse the raw incoming data until it is in a format suitable for sharing. The infrastructure, depending on the size of the data, should always produce a storage size greater than the data. The digital infrastructure should be managed by one organization agreed on by the consortium of stakeholders and RI developers. There are number of such platforms in existence and the lessons learnt from these and best available practices should be applied in the development of these systems

5.3 Data management, analysis, and modelling

5.3.1 Data management

The RI should have a data management portal that offers services for visualization and analysis of data. The data infrastructure should be an open-access data platform allowing all the relevant stakeholders to access and use the data. For convenience the processed data should be grouped according to the RI themes and the EBVs that are under consideration. There should be a standardised way of handling data across all the biodiversity monitoring stations. The proposed RI can adopt a data management structure similar to that of carbon exchange observation and atmospheric composition RIs whereby there would be central facilities for data quality assurance and data centres for storage of data. The diagram below shows a potential standardized way of handling data.

5.3.2 Modelling

The RI should make use of relevant model outputs for areas where true observations are limited. Models should be used to generate data that covers a large area, especially because in-situ observations are generally point observations. In-situ measurements should be used to verify the model data. *In-situ* data should have the capacity to verify the models. Models of biodiversity and ecosystem function are critical to our capability to predict and understand responses to environmental change. There are a variety of modelling approaches which address different biological levels, such as individual-level models and evolutionary adaptation, species- or population-level models, community-level models, ecological interaction networks, and ecosystem-level models and integrated assessment models. .

5.3.3 Data storage or repositories

Copies of all data products handled by data management should be stored in a safe, long-term manner in the infrastructure repository. Long-term existing biodiversity stations can be used as an example and demonstrate how they store and manage their data and further propose that in the future RI can adopt the same strategy. There are many organisations that produce and manage these types of data and one can look at the LTER networks as an example of how this is done in regional and international networks (Knapp et al. 2012; Mirtl et al. 2018; Loescher et al. 2022; Vanderbilt et al. 2015) The data stored should always follow the FAIR principle; Findable, Accessible, Interoperable and Reusable. All the datasets archived or published should always be accompanied by the metadata.

5.3.4 Data sharing and reuse

To successfully manage the data, the RI should have a license in place with terms and conditions that all users agreed to. The license should allow the users to share and adapt the data under certain terms and conditions. The terms and conditions of the license should emphasise the use of proper reference and citation of the data. Users should also inform the providers when they have used the data for publication.

5.4 Knowledge management, skills and capacity building

5.4.1 Knowledge exchange

RI products should be showcased in different platforms such as conferences and interviews. Knowledge can also be shared via publishing research papers and policy briefs. RI should have outreach programs that involve school and community visits to educate people about the RI and share its outputs in a language that they would understand.

5.4.2 Knowledge preservation

RIs can implement structured and deliberate strategies to preserve and manage the outputs, data, methodologies, and intellectual contributions produced through their activities. This effort is essential for ensuring the long-term accessibility, usability, and integrity of these resources, thereby supporting ongoing scientific progress, expanding knowledge, and strengthening the reliability of climate-related actions.

5.4.3 Skill development or capacity building

Everyone that is responsible for operating the RI should be sufficiently trained, that would improve the quality of data as less mistakes will be expected to occur. Data curators should also get training on how to manage the data. This means there should be regular training as equipment and technology are known to change with time. Users should also be trained on how to access and use the data.

5.4.3.1 Scientific capacity

The expertise and knowledge base for researchers and academics to use the RI effectively include training in interdisciplinary fields such as biogeochemistry, ecology, climate and atmospheric sciences as well as appropriate statistical, computational and modelling skills for handling and analysing large data sets. A comprehensive approach that incorporates multidisciplinary education, specific training programs, and improved data science abilities is needed to build scientific capacity for researchers to use Research Infrastructure (RI) in interdisciplinary fields. This includes providing training in coding and statistical analysis, and big data management in addition to training in biogeochemistry, ecology, and data analytics through modular workshops, online courses, and certificates. While promoting collaborative research networks through cross-institutional projects and conferences fosters information sharing, joint degrees, research fellowships, and internships can develop multidisciplinary expertise. Researchers are also guaranteed to be prepared to use RIs efficiently if they invest in practical RI training, provide thorough guides, and receive soft skills training in project management and communication.

5.5 Users and collaborative networks

5.5.1 Stakeholder, actors, and community

All the interested and affected stakeholders should be involved. Their roles and responsibilities should be clearly communicated.

5.5.2 Stakeholder actors and community engagement

There should be stakeholder engagements such as conducting workshops, interviews, one-on-one where the outcomes of the RI will be shared. These engagements could improve the knowledge of the stakeholders.

5.5.3 Feedback mechanisms

Stakeholders should be given a platform to comment, suggest, and evaluate the RI. There should then be a systematic way (whether it's interviews, workshops, surveys etc.) of responding to their comments and suggestions. This will ascertain stakeholders that their voices are heard and taken into consideration and thus promoting trust and long-lasting relationships. In a practical sense this would require the types of governance structures that elicit feedback and continuous improvement of the RI

5.5.4 Dissemination and accessibility

The RI outputs should be disseminated in various ways available. For example, publication of research papers. A good record should be kept of published reports, policy briefs, newsletters and social media posts. The use of local languages should be promoted especially in the local newsletters. This will enable the outcomes to reach all the relevant stakeholders.

5.6 Government and compliance

5.6.1 Standards, policies, and ethical consideration

There should be a set of principles, guidelines, and practices to govern the planning, development, operation, and dissemination of RI activities, with good ethical practices. In the stages where, human engagement is required especially the community members, ethical clearance should be obtained. The outputs should meet the government standards for each theme. Although there is a comprehensive policy, and legal framework in place for conserving biodiversity and ensuring its sustainable use in South Africa, there are many gaps in relation to its implementation. Various hurdles are faced by institutions, including a lack of funding, high staff turnover, and skills gaps. Legislation that is in line with national legislation are at different stages in different provinces, calling for improved co-operation and support for local government.

6 Earth system models research infrastructure

This section covers an Earth System Model research infrastructure.

6.1 Foundation characteristics

6.1.1 Theory of change

The Earth System Model (ESM) research infrastructure would enable the verification and improvement of ESMs. Earth System Model development requires access to quality-controlled observations, for the purpose of model verification, and subsequent model improvement. Limited verification of ESMs in Africa may result in the development of significant biases in the representation of the modelled processes to quantify the carbon sequestration, coastal greenhouse gas flux, ocean acidification and productivity of oceans. The data from in-situ observations would thus support the verification and improvement of ESMs in Africa.

6.1.2 Products, solutions and outputs

Earth System Models have become the main tools to project future climate change, thereby informing on climate change adaptation and exploring the consequences of different mitigation scenarios. Earth System Model simulations can also, through inverse modelling, inform the optimal design of observational networks.

The proposed RI should produce outputs to all interested stakeholders in different forms, for example, publications by researchers in peer-reviewed journals using the data from the RI, booklets, and newsletters. Data from the observation networks should enable researchers to develop and answer research questions, and communicate those findings through research papers, conference presentations, and workshops. Outputs from the RI should, furthermore, enable the government to make informed decisions concerning ESMs in Africa. These decisions can be communicated via policy briefs.

6.1.3 Impact pathways

For the proposed ESM RI to achieve its aims; the following aspects should be considered:

6.1.3.1 Co-design

All the relevant and interested stakeholders should come together to plan and design the RI. This entails:

- Planning where the network of stations should be deployed
- Deciding on what the key variables to be measured are
- Who is going to finance the RI? When considering the financial aspects important things to consider include whether it is going to be funded by all the interested organizations or only one organization, and what are the benefits for both options
- Invite all the potential output users to contribute to the design for their needs to be met.

- Technical maintenance – who is going to be responsible for this, and how all the involved parties are going to benefit at the end.

Co-design minimizes the chances of missing crucial components of the RI, whilst promoting trust and transparency between all parties involved.

6.1.3.2 Ground-based measurements and measurement traceability.

The observational networks required for model development processes include weather stations, flux towers, upper air soundings and oceanic-based observations.

6.1.3.3 Data analysis

Data should be uniformly stored in a reliable database, and analysed using the appropriate analysis tools. Uniformly storing data would enhance easy usage and analysis by various people. The data should also be made available in raw and processed formats to allow free access to any other scientist interested in the data. The data will be stored with all the necessary metadata, to improve the usability of the data by other researchers

6.1.3.4 Validation

The produced data should be used to validate the ESMs.

6.1.3.5 Dissemination of information

The ESM RI should ensure that data is open-access in the data portal of the managing organization. RI output should be disseminated in all applicable ways (i.e. research papers, conferences, workshops, newsletters, and booklets).

6.1.3.6 Training on the usage of data

If the RI is managed by a consortium of different organizations, each organization should make it their responsibility to train the data users on data usage. Inadequate knowledge on how to use the data may result in the misuse and misinterpretation of the data. There should be a standard data usage course across all the organizations that will be conducted annually. In cases where the managing organization does not have the capacity to run the course each year, a document with guidelines should be available with contact details for people to reach out when they need clarity on the data.

6.1.3.7 Equip stakeholders with knowledge

All the knowledge obtained from the RI should be shared with all the stakeholders. The knowledge should help the stakeholders to address the issues they are facing.

6.1.3.8 Actions taken based on the knowledge from RI

As the RI intends to overcome certain issues, knowledge generated from it should be incorporated to resolve some, if not all the issues that were of concern during the planning of the RI. Actions should be taken based on the obtained knowledge.

6.1.4 Monitoring, Evaluation and Learning of Impacts

Impacts of the RI should be regularly monitored. This involves meetings between stakeholders to revise what was agreed as the goal of the RI. The stakeholders should use a set of indicators to evaluate the goal or objective of the RI. Participatory Monitoring Evaluation Reflection Learning (PMERL) is a tool that is often used to monitor the activities. This tool can be adopted to monitor the impact of the RI. The tool is self-explanatory, meaning after stakeholders have participated in the development of the RI they should be involved in all the following steps which are monitoring, evaluation, reflection and learning. PMERL gives an opportunity to improve the performance of the RI.

6.1.5 Co-concepts

In every step of establishing the RI, co-design, creation, and production are crucial. All the relevant or interested stakeholders should be involved in every step; from planning the RI to finally disseminating the product or output. There should be clear understanding who is involved in which stage. It should also be taken into consideration that some stakeholders will join at the later stages.

6.2 Observations, data sources and technologies

6.2.1 Modelling technologies

This section describes the required modelling technologies for the provision of climate services in an integrated manner. It speaks specifically to an Earth System modelling approach which integrates components of atmospheric and climate modelling, a land surface component and an ocean component. It is not in the scope of this document to modelling setups or schemes, but in the context of this report it is necessary to have a model that can address traditional climate scale modelling, with additional integration between the atmosphere, the land surface, the ocean and aspects of chemistry relating to the biogeochemical cycling of C, N and P and the production of aerosols and ozone, in order to address the essential variables that this study focuses on the requirements and needs for the modelling centres and the operational requirements to maintain their function.

6.2.1.1 Earth system modelling centre locations

To ensure that this capacity is maintained on the continent and to support the user needs in the various regions, it is recommended that a number of these facilities would be required in the various regions, preferably representing a combination of Southern, Northern, East and west Africa with regional focus and that develop capacity in operating and supporting at least one of the major earth system models.

6.2.1.2 Required hardware for the Earth Systems Modelling centres

For the integrated Earth System modelling capacity to be achieved there needs to be at least one or more High Performing Computing Facilities (HPC) systems that offer a computational capability of 1Peta byte to run the models. This requires approximately 30 000 CPUs that are dedicated to the earth system modelling activities. Such a facility has specialist requirements, including

- An appropriate building to house the HPC system, this building needs a number of specialist requirements, including
  - A reliable power supply with backup power and load smoothing current control facilities to protect the HPC infrastructure and ensure that the model runs are maintained without interruption.
- Data storage capacity for storing and archiving the model parameterisations and outputs, this should be in the range of 10 Petabytes of storage at present and is likely to be increased in the future as the model resolution increases
- High speed and bandwidth data connectivity is needed by the HPC system to ensure the transfer of input data (if there is some form of data assimilation scheme in operation) and the delivery of products to various servers and data users.

In addition to the physical infrastructure of the HPC hosting facilities, to maintain such a system, it is necessary to have a minimum of 10 full time staff to service the computing facilities, these full-time staff include;

- hardware engineers, for maintaining the infrastructure and the facilities, these staff members need to have appropriate training and qualifications to enable them to build and maintain the computing hardware systems and the electrical supplies and data connectivity.
- Software engineers, these are the staff members that will maintain the operating systems of the HPC systems, the compilers and will provide services in supporting the library of software and the software installations of the various users of the facilities. An HPC with a focus on earth system modelling will typically be running one or more earth system models and their various components.

6.2.1.3 Earth System Model Development

To improve the Earth system modelling capacity in Africa there needs to be a focus on earth system model development, to utilise the capacity for the HPC centres and to utilise the capabilities by working with universities and research institutions. There will need to be the development of research institutions that do model development that are associated with the HPC centres, these institutions will need to be hosted at universities or other research bodies.

In addition to the institutional developments there will need to focus on the development of human capacity development, including;

- Training people with the skills to work on model development,
- Training and developing a core of researchers and students that do earth system modelling

- Development of centres and facilities for training undergraduate students

To keep this going it will require mechanisms for funding through dedicated research calls that may be separate from the core research infrastructure funding provision.

A number of key areas for model development in the near future include: the four main areas of the Earth System Models (Atmosphere, ocean, land surface and chemical transformations), each of these are extensive and require dedicated activities.

The atmospheric component will focus on the modelling of aspects such as radiation, cloud, and cloud microphysics, the turbulence of the atmosphere at varying scales from the micro scale to the synoptic scales, and temporal scales from sub-seconds to multiple decades.

The land surface component, will need to focus on the various biomes and the parameterisation of the vegetation including the plant functional types and albedo, the dynamics surrounding the partitioning and movement of soil moisture, energy exchanges, including the partitioning of the various energy fluxes and the impacts of various disturbances, such as land use changes, impacts of fire and changes to the cryosphere.

In the ocean component this will include need to include a number of aspects such as; ocean biogeochemistry (the exchange of carbon, nitrogen, and other elements), the energy exchanges and fluxes in the ocean, the ocean dynamics, including the ocean currents, thermohaline circulation and the impacts of salinity and variable freshwater inclusions.

The biogeochemical component will focus on modelling the carbon cycle and exchange within and between the atmosphere, the land surface and vegetation, the oceans and the freshwater systems. The impact of changes to the nitrogen cycle, and atmospheric processes leading to aerosol and ozone formation, including the emissions, transformations and deposition of these pollutants and their precursors. Particulate matter may be of particular importance do to its climate, cloud and health impacts. All these aspects will need the availability of accurate emissions inventories. An aspect in the biogeochemical component that may be of importance is how they respond as a projection of potential impacts of solar radiation interventions.

In order to accurately and appropriately develop and run these models, efforts are needed in the improvement of the model inputs for all the model components. For the land component this should focus on the improvement of the land surface characterisation and the vegetation parameterisation, and importantly the improvement of land use and land cover change scenarios. For the atmosphere component this will include improvement in the scenarios for the emissions of GHGs and atmospheric pollutants, including ozone and is precursors. For the aerosol related emissions this should include improvement to the modelling of emission sources such as biomass and waste burning, and dust emissions. In the ocean component an improvement in the description and characterisation of the freshwater fluxes to the oceans, either as prescribed scenarios or assimilation of direct measurements.

6.2.1.4 Model Output dissemination

The dissemination of the model outputs is broad topic and requires dedicated infrastructure and human capacity to support it. Firstly, it requires significant investments in the hard infrastructure, it is estimated that there needs to be at least 10 Petabytes of storage space for the archiving of model outputs. Secondly there needs to be a cohort of trained individuals who can do the model processing, including data scientists who are trained in the climate and earth system sciences and who can then interface with discipline experts and process the model output and provide for the needs of the discipline. Thirdly there needs to be dedicated focus around product development that accounts for the needs of the identified stakeholders and provides products to meet identified needs and predetermined template datasets for various other less defined users. Finally, the products need to be disseminated, this includes the development of platforms for the provision of the data , which will require front end developers. A strategy to marketing to get the potential product users to know of the existence of the systems and products and the support the use of the products.

6.2.1.5 Earth System Modelling Infrastructure upgrades and reinvestment

The infrastructure for earth system modelling is complex, expensive and required regular investments and upgrades to maintain and improve the systems to continue meeting the needs of the modelling and stakeholder communities. This improvement and procurement need to be managed on an approximate 10-year cycles where the whole system is replaces every 10 years, but there is also an upgrade of the existing systems planned in the middle of the cycle

6.2.1.6 Earth System modelling Infrastructure Governance models

The KADI project cannot be prescriptive on the type of governance models that will be employed for the development of the earth system modelling infrastructure. There are however two main that can be used and are being use amongst similar infrastructure globally. The first is where the facilities and infrastructure is held within one institution and the entire development and use cycle is incorporated under the management of that institution, this tends to be the more common model, it has advantages in that this model allows for more efficient use and planning, but it is insular and does not support activities across the wider community.

The second model is where the basic infrastructure is centrally hosted and supported as a shared resource for a broader modelling community. Then through a process of project submissions and approvals and associated funding mechanisms access to the facilities is granted to users from various groups and the infrastructure acts as a shared resource. This may be the more appropriate governance model in the African context, where there is a nascent and fragmented community.

6.2.2 Primary digital data

Primary data refers to all the essential variables that need to be measured by the instrumentation stations. The African-based Earth System Model is generating detailed simulations of climate (Big Data) within project KADI, of value for inverse modelling and research on African climate processes, climate variability and anthropogenically-induced trends in climate.

6.2.3 Secondary digital data

Secondary data is crucial, as it helps the RI to tie its primary data context. Secondary data could be topography, climate, land cover or land use and geology information, and are useful data that can be used to tie with the primary collected data.

6.2.4 Digital infrastructures

The ESM RI should have a digital infrastructure that is suitable for the respective data type. The infrastructure should consist of the tools to analyse the raw incoming data until it is in a format suitable for sharing. The infrastructure, depending on the size of the data, should always produce a storage size greater than the data. The digital infrastructure should be managed by one organization agreed on by the consortium of stakeholders and RI developers.

6.3 Data management, analysis and modelling

6.3.1 Data analysis

The RI should have a data management portal that offers services for visualization and analysis of data. The data infrastructure should be an open-access data platform allowing all the relevant stakeholders to access and use the data. For convenience the processed data should be grouped according to the RI themes. There should be a standardized way of handling data across all the monitoring stations. The proposed RI can adopt a data management structure similar to that of carbon exchange observation and atmospheric composition RIs whereby there would be central facilities for data quality assurance and data centres for storage of data. The diagram below shows a potential standardized way of handling data.

6.3.2 Modelling

The RI should make use of relevant model output for areas where true observations are limited. Models should be in spatial analysis over a large area, especially because in-situ observations are generally point observations. In situ data should be used to verify the model data. The models in turn will provide projections of future climate change.

6.3.3 Data storage or repositories

Copies of all data products handled by data management should be stored in a safe, long-term manner in the infrastructure repository. Here we can use the long-term existing stations as an example and demonstrate how they store and manage their data and further propose that the future RI can adopt the same strategy. For example, if the station supplies data to world data centres and the local database, the proposed station or networks can adopt the same strategy. The data stored should always follow the FAIR principle; Findable, Accessible, Interoperable and Reusable. All the datasets archived or published should always be accompanied by the metadata. Data infrastructure should produce a certain storage space (e.g. 25- 30 TB) per year depending on the amount of data produced.

6.3.4 Data sharing and reuse

To successfully manage the data, the RI should have a license in place with terms and conditions that all users agree to. The license should allow the users to share and adapt the data under certain terms and conditions. The terms and conditions of the license should emphasize the use of proper reference and citation of the data. Users should also inform the providers when they have used the data for publication.

6.4 Knowledge management and skills building

6.4.1 Knowledge exchange

RI products should be showcased in different platforms such as conferences and interviews. Knowledge can also be shared via publishing research papers and policy briefs. There should be outreach programs that involve school and community visits to educate people about the RI and share its outputs in a language that they would understand. For example, the Earth System Model simulations, and new insights gained in terms of land-atmosphere fluxes, will be shared with the scientific community through the usual methods of scientific papers and conference proceedings.

6.4.2 Knowledge preservation

RIs can implement structured and deliberate strategies to preserve and manage the outputs, data, methodologies, and intellectual contributions produced through their activities. This effort is essential for ensuring the long-term accessibility, usability, and integrity of these resources, thereby supporting ongoing scientific progress, expanding knowledge, and strengthening the reliability of climate-related actions.

6.4.3 Skill development or capacity building

Everyone that is responsible for operating the RI should be trained, that would improve the quality of data as less mistakes will be expected to occur. Data curators should also get training on how to manage the data. This means there should be regular training as equipment and technology are known to change with time. Users should also be trained on how to access and use the data.

6.5 Users and collaborative networks

6.5.1 Stakeholder, actors and community

All the interested and affected stakeholders should be involved. Their roles and responsibilities should be clearly communicated. The RI should co-design the establishment of the ESM RI with all the actors in this discipline/field. Engagement could be taken in the form of open and targeted workshops, online and in person.

6.5.2 Stakeholder actors and community engagement

There should be stakeholder engagements such as conducting workshops, interviews, one-on-one where the outcomes of the RI will be shared. These engagements could improve the knowledge of the stakeholders. The stakeholders to climate change projections are extremely broad, stretching across all sectors and all spheres of government, national and international. The African-based Earth System Model serves, first and foremost, African societies and the environment.

6.5.3 Feedback mechanisms

Stakeholders should be given a platform to comment, suggest, and evaluate the RI. There should be a systematic way (whether it's interviews, workshops, surveys etc.) of responding to their comments and suggestions. This will ensure stakeholders that their voices are heard and taken into consideration and thus promote trust and develop long-lasting relationships.

6.5.4 Dissemination and accessibility

The RI outputs should be disseminated in various ways available. A good record should be kept of published reports, policy briefs, newsletters and social media posts. The use of local languages should be promoted especially in the local newsletters. This will enable the outcomes to reach all relevant stakeholders.

6.6 Government and compliance

6.6.1 Standards, policies and ethical consideration

There should be a set of principles, guidelines and practices that govern the planning, development, operation and dissemination of RI activities, with good ethical practices. In the stages where human engagement is required, especially the community members, ethical clearance should be obtained. The outputs should meet the government standards.

7 Research Infrastructure for Coastal Biogeochemistry

This section outlines a pan-African research infrastructure that focuses on coastal biogeochemistry. This aspect formed part of one of the KADI Pilots and incorporates lessons learned in the stakeholder and actor engagement and the deployment of the instrument demonstrators.

7.1 Foundation characteristics

7.1.1 Theory of change

The research infrastructure that focuses on marine biogeochemistry would support the quantification of carbon sequestration, coastal greenhouse gas flux, ocean acidification and productivity of oceans. This information is vital for understanding and prediction of climate drivers and the climate services that this understanding supports. It would further enable climate service needs of different sectors such as mining, oil and gas, fisheries and shipping to be addressed. The data from the coastal biogeochemistry RI should help decision makers to formulate appropriate environmental policies to lessen the risk and vulnerability of the coastal zone to climate and global change (Dai et al. 2022). The RI should improve ecosystem and human health, and advise policy on sea-level rise and storm surges, and early warning system and forecasting of hazardous marine events. Overall, the data from the RI should support adaptation to and mitigation of climate change.

7.1.2 Products, solutions and outputs

The proposed RI should produce its outputs in different forms. There should be publications by researchers using the data from the RI. The data from the observation networks should enable researchers to answer research questions, and communicate those findings through research papers, conference presentations, workshops etc. The outputs of the RI should also enable the government and other regional and international bodies to make informed decisions with regards to coastal biogeochemical processes in Africa. Those decisions can be communicated via policy briefs etc. Moreover, the outputs should also be communicated in any form (such as booklets, newsletters etc.) to interested stakeholders and actors.

7.1.3 Impact pathways

For the proposed marine RI to achieve its intended impacts; the following should be considered in:

7.1.3.1 Co-design

The design of the infrastructure should have the input of all relevant stakeholders and actors at the scale in which they operate, from local, to national and continental. This entails planning where the network of stations should be deployed, what are the key variables to be measured and why, who is going to finance the RI. Modalities of funding and the consequential organisational structures of these infrastructures is out of the scope of this report, however broad level design options range from a consortium of interested organizations funding the infrastructure or components of the infrastructure, or one organization which takes responsibility for the entirety of the development. This will have important impactions on the design process Co-design improves the chances that all essential design aspects and components are accounted for and enhances the buy-in from the various stakeholders and actors.

7.1.3.2 Ground based measurements and measurement traceability.

The RI should have a couple of core sites around the coast of Africa to keep the network in place. Measurements such as those of dissolved organic carbon and carbon isotopes can be taken from water samples to determine the carbon efflux from the monitoring sites. Measurements of pH, total alkalinity and pCO_2 to determine ocean acidification and measurements of phytoplankton and zooplankton diversity and biomass to determine ocean production. The observation system usually consists of fixed stations, research vessels, commercial vessels, moorings, buoys and sometimes voluntary observatory ships.

7.1.3.3 Data analysis

Data should be stored in a reliable database, and/or uploaded to international databses, and analyzed using appropriate analysis tools. The data should also be made available in raw and processed formats to allow free access to any other scientist interested in the data. To improve uptake of the data by coastal managers and policy makers, data products (graphs, maps, etc.) should be developed and made freely available.

7.1.3.4 Validation

The produced data should be used to validate remote sensing data. For example, in addition to ground-based measurements what remote sensing technique/s could be used to estimate the ocean carbon fluxes and other gases and ocean productivity across Africa? Those remote sensing techniques can be validated using the in-situ data.

7.1.3.5 Dissemination of information

Data should be openly and freely accessible in the data portal of the managing organization. Information should be disseminated in all applicable ways (i.e. research papers, conferences, workshops, newsletters, booklets, policy briefs etc.).

7.1.3.6 Training on usage of data

If the RI is managed by a consortium of different institutions, each institution should make it their responsibility to train the data users on how to use the data. Inadequate knowledge on how to use the data may result in the misuse and misinterpretation of the data. There should be a standard data use course across all the institutions that will be conducted annually to ensure the data collection and anlyses remain aligned to international best practices.

7.1.3.7 Equip stakeholders with knowledge

All the knowledge obtained from the RI should be equally shared with the stakeholders. The knowledge should assist the stakeholders to address the challenges they are facing in managing marine resources in the face of global environmental change.

7.1.3.8 Actions taken based on the knowledge from RI

As the RI intends to overcome the initial challenges in rolling out a GHG Observation network, the knowledge generated from it should be able to resolve some, if not all, the challenges that the rest of Africa would face in rolling out a continent wide version of the RI. Actions should be taken based on the knowledge obtained during the pilot phase. For instance, the pilot RI is testing various methods with different cost implications and the final design of the African network will be determined, in part, by the availability of funding.

7.1.4 Monitoring, Evaluation and Learning of Impacts

The impact of the RI should be regularly monitored. This involves bringing together the stakeholders to revise what was agreed to be the goal of the RI. The stakeholders should use a set of indicators to evaluate the goal or objective of the RI. Participatory Monitoring Evaluation Reflection learning (PMERL) is a tool that is often used to monitor the activities. This tool can be adopted to monitor the impact of a RI. After stakeholders have participated in the development of the RI they should be involved in all the following steps that include monitoring, evaluation, reflection and learning. PMERL gives an opportunity to improve the performance of the RI over its lifespan.

7.1.5 Co-concepts

In every step of establishing the RI, co-design, creation, and production is critical. All the relevant or interested stakeholders should be involved in every step; from planning of the RI to finally disseminating the product or output. There should be clear understanding of who is involved in which stage or phase of the RI. It should also be taken into consideration that some stakeholders will join at the later stages, and those stakeholders should also be consulted and included.

7.2 Observations, data sources and technologies

7.2.1 Observations, measurements and monitoring

For a RI in support of Coastal Biogeochemical research, the sites to deploy the network of observatories should be strategically selected. These sites should cover the diversity of the marine environment across Africa and ideally fill critical gaps in information .

A review of existing RI should first be done to obtain the spatial distribution of the existing networks and data availability, although there are currently very few observation sites. New stations should then be deployed in areas of interest where there are gaps in the regional networks. The exact location of the proposed RI should be determined by the practical considerations such as access, marine habitat, presence of existing infrastructure, availability of human resources and other aspects. Measurements that should be taken at the different stations should possibly include all the essential variables identified by Lopez-Ballesteros et al 2018. And should include the observation of Essential Ocean Variables (EOVs), Essential Biodiversity Variables (EBVs) and Essential Climate Variables (ECVs) at fixed and discreet stations around the coast of Africa. Fixed stations could include the deployment of near real-time MetOcean observations moorings. Additionally, GHG measurements such as CO_2, CH_4, N_2O fluxes could be measured from the soil/water/vegetation in key coastal habitats at discreet stations to better understand GHG flux in these habitats. To avoid gaps in data, the stations should be regularly maintained in order to produce quality data. Production of long-term quality data will enable the detection of trends to better understand the impacts and drivers of global change in the marine and coastal environment.

7.2.2 Location of Observations

The African Coastal marine ecosystems have been divided into 8 Large Marine Ecosystems, these include 1) the Mediterranean Sea, 2) the Canary Current, 3) the Guinea Current, 4) the Benguella Current, 5) the Agulhas Current, 6) the Somali Current, 7) the Arabian Sea and 8) the Red Sea region. From the figure below it is clear that five of the eight LMEs have some observations, with the highest concentration in the Agulhas and Benguela Currents LMEs. LMEs with the least observations are the Mediterranean Sea, Red Sea and the Arabian Sea, although observations are extensive on the European coast of the Mediterranean Sea LME. It should be noted though that observations are country specific and several countries within well observed LMEs have no accessible records of observations, e.g. Namibia. The numbers shown in the countries indicate number of sediment cores collected for blue carbon research and many coastal countries in Africa are active in this field, although not all countries or research entities have archived their data (https://shiny.si.edu/coastal_carbon_atlas/). Greenhouse Gas flux measurements (red stars in figure below) are sparser in Africa, and except for South Africa, have mostly been conducted by external research entities that collaborated with local African researchers (Figure 20).

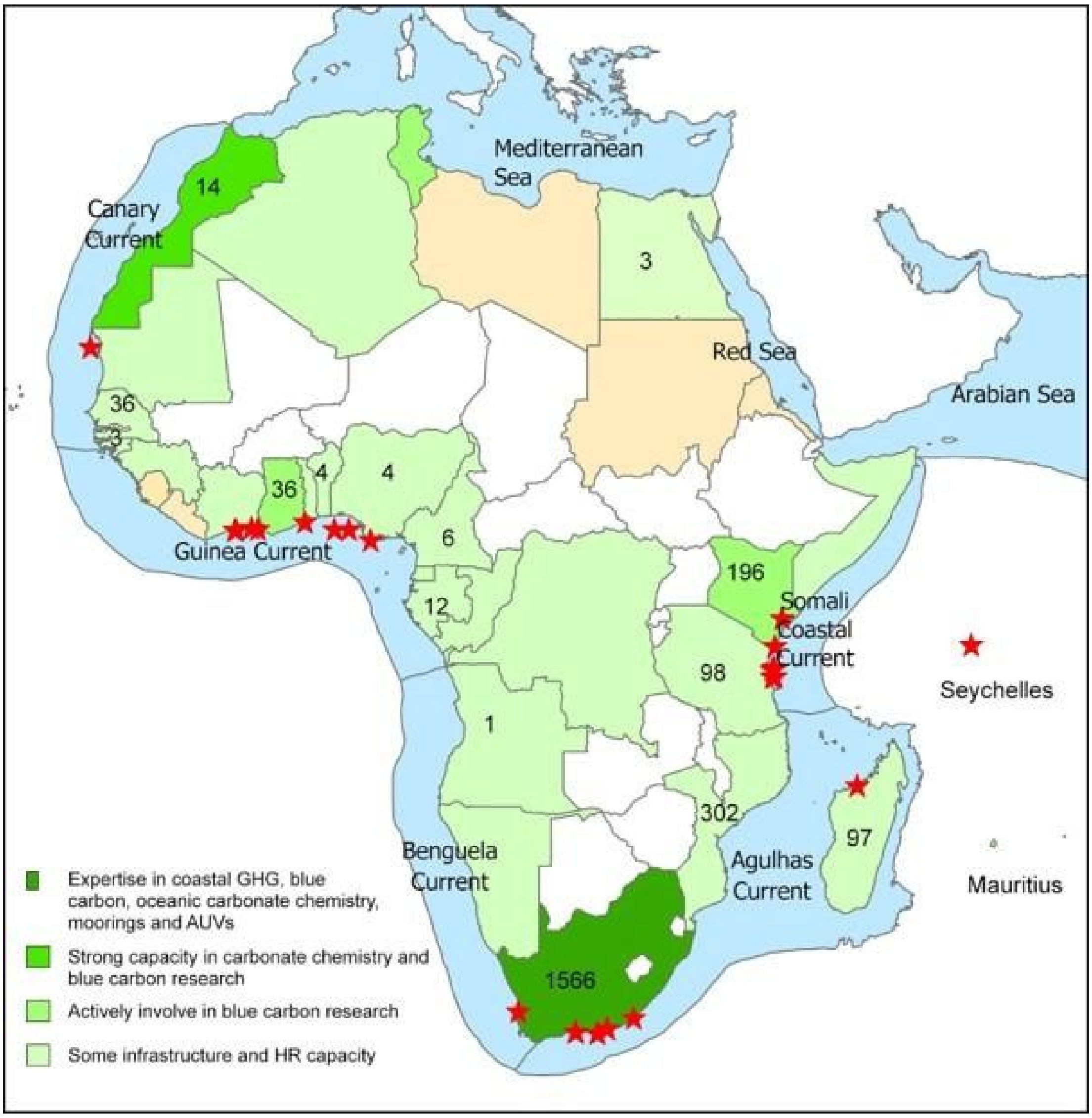

Figure 20 specifications for Coastal Biogeochemical Research Infrastructures in Africa

7.2.3 Parameters to be measured:

A Coastal GHG Observing System that resolves the scales of variability in air-sea flux will need to quantify the carbon budgets in Land-Ocean Aquatic Continuum (LOAC), and constrain the variability and trends of long term GHG fluxes and ocean acidification. Most countries in Africa have the capability and resources to determine coastal wetland (salt marshes, seagrasses, mangroves, etc.) carbon budgets, but the cost and skills required to quantify GHG fluxes and ocean acidification limits the observations to a few countries in Africa. Methods for the determination of blue carbon is well documented (Howard et al. 2014: https://www.thebluecarboninitiative.org/manual and Schindler Murray) et al. 2023: https://oceanpanel.org/wp-content/uploads/2023/06/Ocean_Panel_Blue_Carbon_Handbook-1.pdf) and implemented globally. To be able to produce observational data that can provide ocean biogeochemical forecasts and early warnings and, thus, contribute to climate projections, the global scientific community agreed to measure the biogeochemical Essential Ocean Variables (BGC-EOVs). Currently, BGC-EOVs comprise of the nine variables: oxygen, nutrients, inorganic carbon, Transient tracers, Particulate matter, Nitrous oxide, Stable carbon isotopes, Dissolved organic carbon, and Ocean Colour. Comprehensive specification sheets describing each of the variables usage, global observing networks, sensor types, metrology requirements/capabilities etc. can be downloaded from the website of the Global Ocean Observing System (GOOS) https://goosocean.org (see: https://goosocean.org/what-we-do/framework/essential-ocean-variables/). The majority of the BGC-EOVs requires expert scientists and technicians to collect, analyse and interpret the results and only South Africa and Morocco are currently active in this field.

7.2.3.1 Instrument and method specifications:

Following extensive workshops and instrument trials in South Africa, the Coastal Biogeochemistry pilot proposes the adoption of a phased roll-out approach of research infrastructure. The first phase consists of low-cost observational infrastructure that can easily be implemented in most countries in Africa. The second phase involves the procurement of medium cost research infrastructure with limited training required. The third and final phase involves the roll-out of high cost continuous and discreet near-shore observations that require specialised scientists and technicians to implement and maintain.

7.2.3.2 Low-cost blue carbon observatory

Large focus on developing low cost techniques that deliver high quality data:
Specifications:

- Sediment and vegetative carbon pools of salt marsh, mangroves, sea grasses, etc:
    - Sediment corers, e.g. Russian Peat / Sediment Corer (e.g. https://www.vanwalt.com/equipment/russian-peat-corer-set/)
    - Drying oven
    - Ashing oven
    - Consumables, e.g. crucibles
- Rod-Set-Elevation Tables (sediment elevation change)
    - Rods, receivers, SET (https://www.usgs.gov/centers/eesc/science/surface-elevation-table)
- Remote sensing (vegetation density, canopy height, etc.)
- Ocean acidification (GOA-ON-in-a-Box)
    - https://www.goa-on.org/resources/kits.php
- Biogeochemistry (Coastal-Lab-in-a-Box)
    - https://pogo-ocean.org/innovation-in-ocean-observing/activities/coastal-observing-lab-in-a-box-colab/

Staffing: Existing staff, technicians and students

Calibration: Limited calibration required except for GOA-ON in a Box and Coastal Lab in a Box, but programmes provide support.

Supplier support: Suppliers provide support throughout Africa and from regional centres.

7.2.3.3 Estuarine / freshwater carbon observatory (Medium cost)

- GHG-flux observations through chamber measurements
  - Flux chambers, e.g. https://www.licor.com/products/soil-flux
  - Real-time flux calculations when connected to Gas Analysers for CO_2, CH_4, and/or N_2O measurements.
  - Static flux chamber for sediment-atmosphere boundary gas exchange determination.
  - Dark and transparent chamber deployments = respiration & net ecosystem exchange
  - Pore-water dissolved concentrations
  - Diffusive flux at water-air interface
  - Quantifying the emission pathways & seasonality in trace gas fluxes from coastal habitats:
  - Diffusion, ebullition & plant-mediated transport = net ecosystem GHG flux
- Measurement of water and soil carbon species (DIC, DOC, TOC, PIC, POC, etc.) using CNS elemental analysers
  - CNS analyser, e.g. https://www.elementar.com/en/products/organic-elemental-analyzers
  - TOC analyser, e.g. https://www.elementar.com/en/products/toc-analyzers

Staffing: Specialised biogeochemical laboratory technicians
Calibration: Regular calibration and serving of instruments required. Five-year maintenance plans on all instrumentation recommended.
Supplier support: Suppliers available in all regional centres in Africa, but major repairs and calibration will require shipping outside of the continent.

7.2.3.4 Near-shore GHG Observatory (High cost)

Fixed stations – continuous measurements

- Shallow near-shore mooring deployments
- Mooring must observe the following variables:
  - Sea surface pCO_2; Temperature, salinity, pressure, 1 of (TA, DIC), pH, Dissolved Oxygen, 2 of (NO_3, PO_4, $Si(OH)_4$)
  - Additional variables that are desirable: Chl-a, turbidity, currents strength and direction, pCO_2 in the air, surface climate (wind direction and speed, rainfall, barometric pressure, etc.)
  - Frequency: At least 1 per day (ideally once per hour)
- Ancillary requirements to service mooring and data holdings
  - Research SCUBA dive team for maintenance
  - Research vessel to access mooring

    - Online real-time database and data archiving centre

Fixed stations – discreet measurements

- Water samples collected at fixed stations in the nearshore at regular intervals over the long term
- Variables to sample:
    - Temperature, salinity, 2 of (NO_3, PO_4, $Si(OH)_4$), DO, pressure, 2 of (DIC, TA, pCO_2, pH)
    - Desirable: Chl, DOC, N_2O, CH_4, CDOM, phytoplankton and zooplankton
    - Frequency: 1/year or 1/month (ideally monthly)
- Ancillary requirements to service mooring and data holdings
    - Research vessel to access stations
        - Davit/crane to launch instruments and nets
        - CTD (e.g. https://www.seabird.com/profiling/family?productCategoryId=54627473767)
        - 20 / 55 µm mesh phytoplankton ring net
        - 90 and 200 µm zooplankton bongo net
        - Freezer/fridge space onboard
    - Laboratories to analyse chl-a, nutrients, Carbon (DIC, DOC, etc) and plankton (phytoplankton and zooplankton)
    - Online database and data archiving centre

Staffing: Specialised skippers, sea-going technicians, scientific divers and supervisors, biogeochemical laboratory technicians, oceanographic scientists and biogeochemical scientists
Calibration: Regular calibration of seagoing instruments and laboratory instruments.
Supplier support: Suppliers available in all regional centres in Africa, but major repairs and calibration will require shipping outside of the continent.

7.2.4 Support required:

A long-term ambition of the project is to put in place autonomous observing systems to track carbon fluxes and other GHG's in the coastal region, ultimately extending to include the coasts of east, west and north Africa incorporating important upwelling systems and western boundary currents, which support rich a fisheries industry and substantive air-sea CO_2 flux. Such observing systems need to be robust, use common standards, be well calibrated, capable of delivering data in near real time in support of both international climate policy development and domestic management of ecosystem services. This will ultimately be achieved with the assimilation of data into high resolution ocean-atmosphere coupled models with tangible implications for improved climate projections that will benefit society in accordance with adaptation and mitigation strategies through policy implementation. To interpret the observed data correctly, often other supporting variables such as temperature and salinity need to be measured. Moreover, for any African network to produce accurate data that satisfy the requirements of international standards, access to calibration facilities is a must. Furthermore, human resource-wise, this task requires skilled personnel with minimum oceanographic knowledge and weeks to months long instrument-specific technical and laboratory technique courses depending on the variables in question.

7.2.5 Primary digital data

This speaks to all the essential ocean variables that need to be measured in the instrumentation stations. According to Lopez-Ballesteros et al., 2018 the variables that could be prioritized include but are not limited to zooplankton and phytoplankton biomass and diversity, ocean surface heat flux, sea level, sea surface temperature, inorganic carbon, nutrients, and marine habitat properties. What instruments or methods are used to monitor or measure these variables? The near-real time moorings could be used to collect hourly data on water column pCO_2, temperature, salinity, pressure/depth, pH, DO, NO_3, Chl-a, turbidity & surface met climate.

Measurements of dissolved organic carbon and carbon isotopes from water samples to determine the carbon efflux. Measurements of pH, total alkalinity and pCO_2 to determine ocean acidification and measurements of phytoplankton and zooplankton diversity and biomass to determine ocean production.

7.2.6 Secondary digital data

Secondary data is crucial as it helps the RI to tie its primary data into context. Secondary data could be the remote sensing data that would further be validated by the in-situ data. Remote sensing techniques that can be validated by the in-situ marine data, include weather data from weather services, river or stream flow data, and ocean forecasts and predictive models. Additionally, geospatial data can be combined with all the primary data to find the locations that will be most impacted by for instance ocean acidification and other processes.

7.2.7 Digital infrastructures

The RI with the marine focus should have a digital infrastructure that is suitable for its data type. The infrastructure should consist of the tool to analyse the raw incoming data until it is in a format suitable for sharing. The infrastructure depending on the size of the data should always make available storage that are greater than the size of the anticipated data production. The digital infrastructure should be managed by one organization agreed on by the consortium. The data should always adhere to the FAIR principles and be open and freely available in observations databases and data portals.

7.3 Data management, analysis and modelling

7.3.1 Data analysis

The RI should have a data management portal that offers services for visualization and analysis of data. The data infrastructure should be an open data platform allowing all the relevant stakeholders to access and use the data. There should be a standardized way of handling data across all the marine observation stations. The proposed RI can adopt a data management structure similar to that of ICOS oceans, SMCRI and other marine networks whereby there would be central facilities for data quality assurance and data centres for storage of data.

7.3.2 Modelling

The RI should make use of relevant model output for areas where true observations are scarce. Models should be used to develop data that covers a large area, especially because in-situ observations are generally point observations. In situ data should have the capacity and be used to verify the model data. Examples of marine modes include marine forecasts, particle tracking (dispersion models), hydrodynamic models, etc.

7.3.3 Data storage or repositories

Copies of all data and data products handled by the data management should be stored in a safe, long-term manner in the infrastructure repository. An example of a long tern database is the SAEON Observations Database and data repository, where all the pilot study data are and will be stored and managed and it is proposed that the future RI can adopt a similar strategy. The SAEON data complies with the FAIR principles , has received a CoreTrust Seal and the databases are lined to global data centres and it is proposed that the future continental RI adopt the same strategy. The data stored should always follow the FAIR principle, i.e. Data must be Findable, Accessible, Interoperable and Reusable. All the datasets archived or published should always be accompanied by appropriate metadata. Data infrastructure should be designed to data production, archiving of the raw data and various levels of processing and it should be backed up off site.

7.3.4 Data sharing and reuse

To successfully manage the data, the RI should have a license in place that users will have to agree to its terms and conditions. The license should obviously allow the users to share and adapt the data under certain terms and conditions. The terms and conditions of the license should emphasize the use of proper references and citation of the data, including any DOIs minted.

7.4 Knowledge management and skills building

7.4.1 Knowledge exchange

RI products should be showcased or shared in different platforms such as interviews, workshops, presentations at conferences, reports, popular articles and targeted meetings. Knowledge can also be shared via publishing research papers, policy briefs etc. The RI should have outreach programs that involve school and community visits to educate society about the RI and share its outputs.

7.4.2 Knowledge preservation

The Coastal Biogeochemistry RI should implement structured and deliberate strategies to preserve and manage the outputs, data, methodologies, and intellectual contributions produced through their activities. This effort is essential for ensuring the long-term accessibility, usability, and integrity of these resources, thereby supporting ongoing scientific progress, expanding knowledge, and strengthening the reliability of climate-related actions.

7.4.3 Skill development or capacity building

Everyone that is responsible for operating the RI should be trained, which will improve the quality of data collected as less mistakes will be expected to occur. Data curators should also receive training on how to manage, quality control, archive and disseminate the data. This means there should be regular training as equipment and technology are known to change and evolve with time. Users should also be trained on how to access, analyse and use the data.

7.5 Stakeholder, actors and community

All the interested and affected stakeholders should be involved. Their roles and responsibilities should be clearly communicated. The RI should co-design the establishment of a coastal RI with all the actors in this discipline/field. Engagement could be taken in the form of open and targeted workshops online and in person.

7.5.1 Stakeholder actors and community engagement

This section is similar to the co-concept section. There should be stakeholder engagements such as conducting workshops, interviews and , one-on-one discussions where the outcomes of the RI will be shared. These engagements could improve the knowledge of the stakeholders.

7.5.2 Feedback mechanisms

Stakeholders should be given a platform to comment, suggest, and evaluate the RI. There should then be a systematic way (whether it’s interviews, workshops, surveys etc.) of responding to their comments and suggestions. This will ascertain stakeholders that their voices are heard and taken into consideration and thus promoting trust and long-lasting relationships.

7.5.3 Dissemination and accessibility

The RI outputs should be disseminated in various ways available. For example, publication of research papers, reports, policy briefs, newsletters and social media posts. The use of local languages should be promoted especially in the local newsletters. This will enable the outcomes to reach all the relevant stakeholders. In addition, data should be shared with other large RI’s and global networks, e.g. ICOS, GERI, ILTER (DEIMS database) to increase access and impact of the data. Access to the research infrastructure should be open and free.

7.6 Government and compliance

7.6.1 Standards, policies and ethical consideration

There should be a set of principles, guidelines and practices that govern the planning, development, operation and dissemination of RI activities, with good ethical practices. In the stages where human engagement is required, especially involving community members, ethical clearance should be obtained. The outputs should meet the government standards, e.g. coastal and environmental management acts, research permitting requirements, etc.

7.7 Opportunities for Citizen Science or Community based observations in the RI

7.7.1 Commonalities among the various research infrastructure themes

The designed pan African research infrastructures intend to produce outputs that would enable researchers to answer certain research questions and the government to make informed decisions. The outputs will be communicated in a similar manner across all the RIs, that being in the form of booklets, newsletters and other relevant media to all the interested stakeholders. Data management is another key common component among all the RIs. All the RIs aim to manage data in a similar manner; they intend to have a data management portal that offers services for visualization and analysis of data. The data infrastructure will be an open data platform allowing all the relevant stakeholders to access and use the data. For convenience, the processed data will be grouped according to the RI themes. The RIs will have a standardized way of handling data. Data sharing and reuse; RIs will all have the same license in place that users will have to agree to its terms and conditions, appropriate licenses would be the creative commons with attribution, or an equivalent license. The license will allow the users to share and adapt the data under certain terms and conditions. The terms and conditions of the license will emphasize the use of proper referencing, acknowledgement and citation of the data. Users will be requested to inform the providers when they have used the data for publication. The various RIs are envisioned to comply with the applicable government standards, policies and ethical considerations. Similar steps to establish a RI will be taken across all the RI themes. These steps include co-design, co-creation and co-production. This means all the RI themes plan to engage with the relevant stakeholders in all the stages of a RI development.

7.7.2 Existing organizations or projects

7.7.2.1 Existing carbon research infrastructure or projects

Lopez- Ballesteros et al. 2018 provided evidence that there are significant gaps in the carbon related observational network in Africa. At both global and regional scales, the coastal ocean is currently viewed as a sink of atmospheric CO_2 (Chen et al. 2013; Laruelle et al. 2018; Resplandy et al. 2024) with some studies indicating that the CO_2 uptake is intensifying (Dai et al. 2022; Andersson, MACKENZIE, and LERMAN 2005). However, recent results from South Africa (See KADI Deliverable 2.2) indicate that estuaries, situated in the middle of the LOAC are major sources of greenhouse gasses despite being excellent at sequestering and storing large quantities of organic carbon in the plants and the sediment, known as Blue Carbon. Information from the rest of Africa is scarce and this RI proposes to upscale the pilot study in South Africa throughout the region to fill in the gaps in data and information. Most countries in Africa has some capability in carbon research (See KADI Deliverable 2.2. and 4.5), but these entities and projects require additional support and funding to reach their full potential as a RI.

8 Integration of the research infrastructures and impact

The work of KADI project builds on the foundation provided by the previously EU-funded SEACRIFOG project. This work highlighted the need for co-creation in the integration of food security into a conceptual monitoring framework focussed on observations of carbon and greenhouse gas dynamics and air quality measurements to support climate adaptation and mitigation in sub-Saharan Africa.

The task of this deliverable was to develop a comprehensive compilation of envisaged observational networks relate to specific challenges and climate services for Africa. Outputs from multiple stakeholder workshops (as undertaken in WP1) in combination with expert opinion from atmospheric, terrestrial and oceanic thematic areas allowed for the identification of a suite of essential variables that should be considered within, and form part of a future research infrastructure framework to support climate services for Africa. In this deliverable we have utilised the outputs of WP1 developed a comprehensive blueprint for the elements that comprise 5 major research infrastructures that would support climate services in Africa. The design for each of the Ris was based on the a number key elements that each of the that each of the research infrastructures needs to address as determined in the process undertaken during the WP1 development, these were presented in Figure 1 and outlined in section 2. As the stakeholder engagement progressed it was determined that the Research Infrastructure elements concept, while being extremely useful for the development of an individual RI, they are highly hierarchical. The hierarchical network graph does not reveal connections between the elements. For example, *digital infrastructures* are often closely connected to several other elements, such as *knowledge exchange*, *data sharing and reuse*, and *stakeholder, actor and community engagement*. Therefore, the team working on WP1 re-designed the element figure to better represent these interconnections by moving forward from the hierarchical structure (Figure 21). These elements cut across the domains in which the infrastructures interact and four main domains were identified and include 1) the operational domain, 2) the information domain, 3) the knowledge domain and 4) the society domain.

- The **operational domain** focuses on the operation of the infrastructure in terms of the general operations and how the routine tasks of collecting the observations is achieved, the technologies and facilities that are used and the extensive human resources required to maintain and operate the infrastructures. The Operational Domain is the central underpinning element of the climate services research infrastructure and includes the elements of the observations and how they are undertaken in an accurate and sustained manner. This therefore includes aspects of the observations such as;
    - the essential variables that are observed,
    - where they are observed, such as the requirements to ensure that the observations are made in a representative location.

  - the type of technology that is used to observe the essential variable of interest, this speaks to the type and properties of the sensors, and how the sensors maintain appropriate traceability to the chain of national and international meteorological standards tracing to the International SI units and how the uncertainty in each of those measurement steps is quantified, and
  - The technical and scientific staff employed in the RI or utilising the RI to further their own observations. To operate and maintain the measurements and to process the sensor output so that it forms data, there is a requirement for appropriate human resources, in the form of technicians, artisans and scientists. The RI requires these staff and the support for their roles, such as programs to develop staff technical capacity and career development. This should form part of the basic operations of the RI.
- The **information domain** refers to the section of the RI that engages primarily with the data, as it is produced through the operations and how that data is made available for use. Elements of this domain include processes to check and quality control the data, the archiving of the raw and quality-controlled data and relevant metadata. This then feeds into processes of data analysis and the modelling components of a RI.
- The **knowledge domain** refers to the processes of moving from an available dataset to a usable product that can be useful for decision making. Elements in this domain include the dissemination and accessibility of the data products and the ethical and procedural considerations in how this knowledge is transferred to relevant actors and stakeholders.
- The knowledge domain is the outer circle of the conceptual model, where the knowledge is utilised for societal benefit across a wide number of economic and environmental sectors.

The whole concept of how the RIs interact across the domains is highly integrated and engagements between the domains is essential as the RIs evolve to meet the needs and expectations of the relevant actors and stakeholders.

Similarly, the 5 environmental RIs that have been proposed are interdisciplinary and the data, knowledge and societal impact needs to flow between the identified infrastructures. This can be done through ensuring that there is the development of communities of practice within each of these RIs and that the communities of practice engage with each other.

Moving forward clarity will be needed on the funding arrangements for such infrastructures, as this will determine the modes of development and engagement of the infrastructures as they develop across the continent.

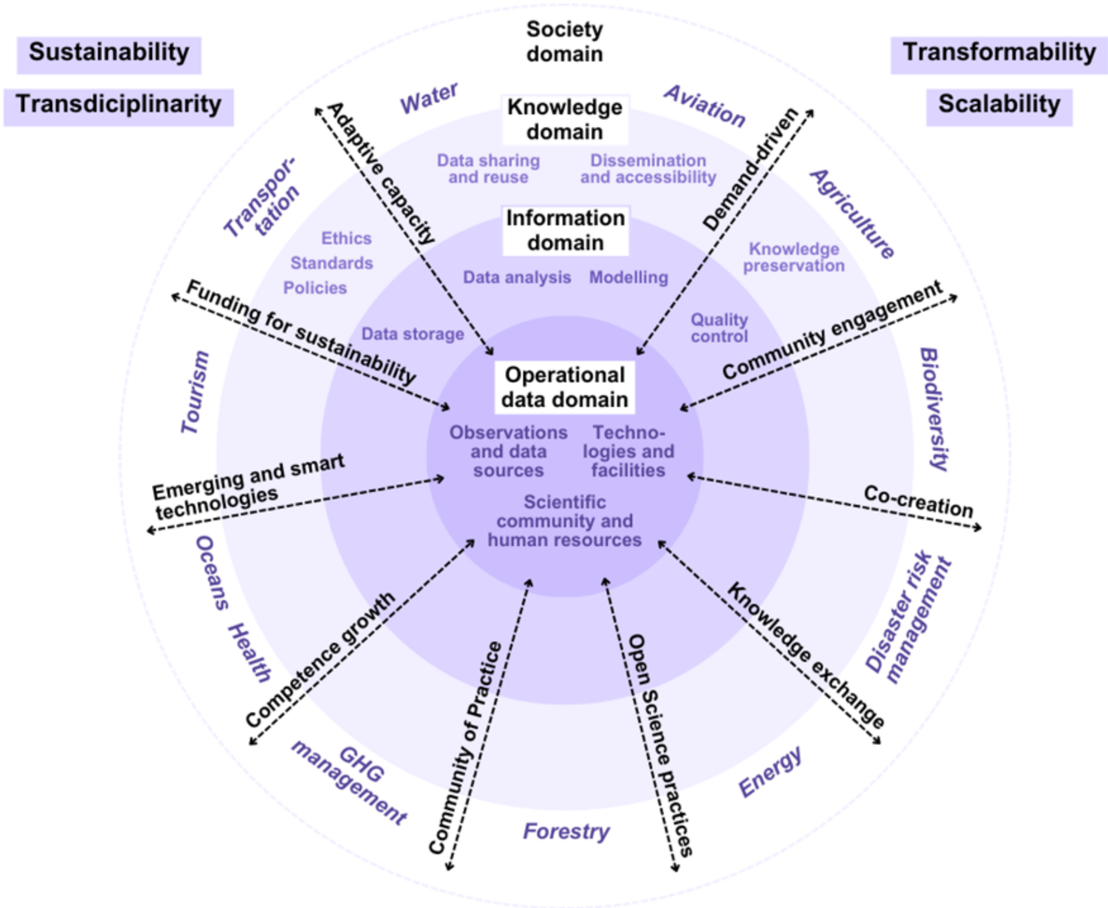

Figure 21 Updated figure for key research infrastructure elements. The figure illustrates interconnectedness of the elements, as well as how the RI impacts evolve towards the society

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Appendix 1: Standardised Parameter Names for Flux Observations

Name	Description	Units
TIMEKEEPING		
TIMESTAMP_START	ISO timestamp start of averaging period (up to a 12-digit integer as specified by the data's temporal resolution)	YYYYMMDDHHMM
TIMESTAMP_END	ISO timestamp end of averaging period (up to a 12-digit integer as specified by the data's temporal resolution)	YYYYMMDDHHMM
TIMESTAMP	ISO timestamp (up to a 12-digit integer as specified by the data's temporal resolution)	YYYYMMDDHHMM
BIOLOGICAL		
DBH	Diameter of tree measured at breast height (1.3m) with continuous dendrometers	cm
LEAF_WET	Leaf wetness, range 0-100	%
SAP_DT	Difference of probes temperature for sapflow measurements	deg C
SAP_FLOW	Sap flow	mmolH_2O m-2 s-1
T_BOLE	Bole temperature	deg C
T_CANOPY	Temperature of the canopy and/or surface underneath the sensor	deg C
FOOTPRINT		
FETCH_70	Distance at which cross-wind integrated footprint cumulative probability is 70%	m
FETCH_80	Distance at which crosswind integrated footprint cumulative probability is 80%	m
FETCH_90	Distance at which crosswind integrated footprint cumulative probability is 90%	m
FETCH_FILTER	Footprint quality flag (i.e., 0, 1): 0 and 1 indicate data measured when wind coming from direction that should be discarded and kept, respectively	nondimensional
FETCH_MAX	Distance at which footprint contribution is maximum	m
GASES		
CH4	Methane (CH4) mole fraction in wet air	nmolCH4 mol-1
CH4_MIXING_RATIO	Methane (CH4) in mole fraction of dry air	nmolCH4 mol-1
CO	Carbon Monoxide (CO) mole fraction in wet air	nmolCO mol-1
CO2	Carbon Dioxide (CO_2) mole fraction in wet air	µmolCO_2 mol-1

CO2_MIXING_RATIO	Carbon Dioxide (CO_2) in mole fraction of dry air	µmolCO_2 mol-1
CO2_SIGMA	Standard deviation of carbon dioxide mole fraction in wet air	µmolCO_2 mol-1
CO2C13	Stable isotopic composition of CO_2 - C13 (i.e., d13C of CO_2)	‰ (permil)
FC	Carbon Dioxide (CO_2) turbulent flux (no storage correction)	µmolCO_2 m-2 s-1
FCH4	Methane (CH_4) turbulent flux (no storage correction)	nmolCH_4 m-2 s-1
FN2O	Nitrous oxide (N_2O) turbulent flux (no storage correction)	nmolN_2O m-2 s-1
FNO	Nitric oxide (NO) turbulent flux (no storage correction)	nmolNO m-2 s-1
FNO2	Nitrogen dioxide (NO_2) turbulent flux (no storage correction)	nmolNO_2 m-2 s-1
FO3	Ozone (O_3) turbulent flux (no storage correction)	nmolO_3 m-2 s-1
H2O	Water (H_2O) vapor in mole fraction of wet air	mmolH_2O mol-1
H2O_MIXING_RATIO	Water (H_2O) vapor in mole fraction of dry air	mmolH_2O mol-1
H2O_SIGMA	Standard deviation of water vapor mole fraction	mmolH_2O mol-1
N2O	Nitrous Oxide (N_2O) mole fraction in wet air	nmolN_2O mol-1
N2O_MIXING_RATIO	Nitrous Oxide (N_2O) in mole fraction of dry air	nmolN_2O mol-1
NO	Nitric oxide (NO) mole fraction in wet air	nmolNO mol-1
NO2	Nitrogen dioxide (NO_2) mole fraction in wet air	nmolNO_2 mol-1
O3	Ozone (O_3) mole fraction in wet air	nmolO_3 mol-1
SC	Carbon Dioxide (CO_2) storage flux	µmolCO_2 m-2 s-1
SCH4	Methane (CH_4) storage flux	nmolCH_4 m-2 s-1
SN2O	Nitrous oxide (N_2O) storage flux	nmolN_2O m-2 s-1
SNO	Nitric oxide (NO) storage flux	nmolNO m-2 s-1
SNO2	Nitrogen dioxide (NO_2) storage flux	nmolNO_2 m-2 s-1
SO2	Sulfur Dioxide (SO_2) mole fraction in wet air	nmolSO_2 mol-1
SO3	Ozone (O_3) storage flux	nmolO_3 m-2 s-1
HEAT		
FH2O	Water vapor (H_2O) turbulent flux (no storage correction)	mmolH_2O m-2 s-1
G	Soil heat flux	W m-2
H	Sensible heat turbulent flux (no storage correction)	W m-2

LE	Latent heat turbulent flux (no storage correction)	W m-2
SB	Heat storage flux in biomass	W m-2
SG	Heat storage flux in the soil above the soil heat fluxes measurement	W m-2
SH	Sensible heat (H) storage flux	W m-2
SLE	Latent heat (LE) storage flux	W m-2
MET_ATM		
PA	Atmospheric pressure	kPa
PBLH	Planetary boundary layer height	m
RH	Relative humidity, range 0-100	%
T_SONIC	Sonic temperature	deg C
T_SONIC_SIGMA	Standard deviation of sonic temperature	deg C
TA	Air temperature	deg C
VPD	Vapor Pressure Deficit	hPa
MET_PRECIP		
D_SNOW	Snow depth	cm
P	Precipitation	mm
P_RAIN	Rainfall	mm
P_SNOW	Snowfall	mm
RUNOFF	Run off	mm
STEMFLOW	Excess precipitation that drains from outlying branches and leaves and is channelled through the stems to the ground	mm
THROUGHFALL	Excess precipitation that passes directly through a canopy or drips from wet leaves to the ground	mm
MET_RAD		
ALB	Albedo, range 0-100	%
APAR	Absorbed PAR	µmolPhoton m-2 s-1
EVI	Enhanced Vegetation Index	nondimensional
FAPAR	Fraction of absorbed PAR, range 0-100	%
FIPAR	Fraction of intercepted PAR, range 0-100	%
LW_BC_IN	Longwave radiation, below canopy incoming	W m-2
LW_BC_OUT	Longwave radiation, below canopy outgoing	W m-2
LW_IN	Longwave radiation, incoming	W m-2
LW_OUT	Longwave radiation, outgoing	W m-2
MCRI	Carotenoid Reflectance Index (Gitelson et al., 2002)	nondimensional
MTCI	Meris Terrestrial Chlorophyll Index (Dash and Curran, 2004)	nondimensional

NDVI	Normalized Difference Vegetation Index	nondimensional
NETRAD	Net radiation	W m-2
NIRV	Near Infrared Vegetation Index (Badgley et al., 2017)	W m-2 sr-1 nm-1
PPFD_BC_IN	Photosynthetic photon flux density, below canopy incoming	µmolPhoton m-2 s-1
PPFD_BC_OUT	Photosynthetic photon flux density, below canopy outgoing	µmolPhoton m-2 s-1
PPFD_DIF	Photosynthetic photon flux density, diffuse incoming	µmolPhoton m-2 s-1
PPFD_DIR	Photosynthetic photon flux density, direct incoming	µmolPhoton m-2 s-1
PPFD_IN	Photosynthetic photon flux density, incoming	µmolPhoton m-2 s-1
PPFD_OUT	Photosynthetic photon flux density, outgoing	µmolPhoton m-2 s-1
PRI	Photochemical Reflectance Index	nondimensional
R_UVA	UVA radiation, incoming	W m-2
R_UVB	UVB radiation, incoming	W m-2
REDCI	Red Edge Chlorophyll Index	nondimensional
REP	Red Edge Position (Dash and Curran, 2004)	nm
SPEC_NIR_IN	Radiation (near infra-red band), incoming (hemispherical)	W m-2 nm-1
SPEC_NIR_OUT	Radiation (near infra-red band), outgoing	W m-2 sr-1 nm-1
SPEC_NIR_REFL	Reflectance (near infra-red band)	nondimensional
SPEC_PRI_REF_IN	Radiation for PRI reference band (e.g., 570 nm), incoming (hemispherical)	W m-2 nm-1
SPEC_PRI_REF_OUT	Radiation for PRI reference band (e.g., 570 nm), outgoing	W m-2 sr-1 nm-1
SPEC_PRI_REF_REFL	Reflectance for PRI reference band (e.g., 570 nm)	nondimensional
SPEC_PRI_TGT_IN	Radiation for PRI target band (e.g., 531 nm), incoming (hemispherical)	W m-2 nm-1
SPEC_PRI_TGT_OUT	Radiation for PRI target band (e.g., 531 nm), outgoing	W m-2 sr-1 nm-1
SPEC_PRI_TGT_REFL	Reflectance for PRI target band (e.g., 531 nm)	nondimensional
SPEC_RED_IN	Radiation (red band), incoming (hemispherical)	W m-2 nm-1
SPEC_RED_OUT	Radiation (red band), outgoing	W m-2 sr-1 nm-1
SPEC_RED_REFL	Reflectance (red band)	nondimensional
SR	Simple Ratio	nondimensional
SW_BC_IN	Shortwave radiation, below canopy incoming	W m-2

SW_BC_OUT	Shortwave radiation, below canopy outgoing	W m-2
SW_DIF	Shortwave radiation, diffuse incoming	W m-2
SW_DIR	Shortwave radiation, direct incoming	W m-2
SW_IN	Shortwave radiation, incoming	W m-2
SW_OUT	Shortwave radiation, outgoing	W m-2
TCARI	Transformed Chlorophyll Absorption in Reflectance Index	nondimensional
MET_SOIL		
SWC	Soil water content (volumetric), range 0-100	%
SWP	Soil water potential	kPa
TS	Soil temperature	deg C
TSN	Snow temperature	deg C
WTD	Water table depth	m
MET_WIND		
MO_LENGTH	Monin-Obukhov length	m
TAU	Momentum flux	kg m-1 s-2
U_SIGMA	Standard deviation of velocity fluctuations (towards main-wind direction after coordinates rotation)	m s-1
USTAR	Friction velocity	m s-1
V_SIGMA	Standard deviation of lateral velocity fluctuations (cross main-wind direction after coordinates rotation)	m s-1
W_SIGMA	Standard deviation of vertical velocity fluctuations	m s-1
WD	Wind direction	Decimal degrees
WD_SIGMA	Standard deviation of wind direction (Yamartino, 1984)	decimal degree
WS	Wind speed	m s-1
WS_MAX	maximum WS in the averaging period	m s-1
ZL	Monin-Obukhov Stability parameter	nondimensional
PRODUCTS		
GPP	Gross Primary Productivity	µmolCO_2 m-2 s-1
NEE	Net Ecosystem Exchange	µmolCO_2 m-2 s-1
RECO	Ecosystem Respiration	µmolCO_2 m-2 s-1
QC_FLAG		
FC_SSITC_TEST	Results of the quality flagging for FC according to Foken et al 2004, based on a combination of Steady State and Integral Turbulence Characteristics tests by Foken and Wichura (1996) (i.e., 0, 1, 2)	nondimensional

FCH4_SSITC_TEST	Results of the quality flagging for FCH4 according to Foken et al 2004, based on a combination of Steady State and Integral Turbulence Characteristics tests by Foken and Wichura (1996) (i.e., 0, 1, 2)	nondimensional
FN2O_SSITC_TEST	Results of the quality flagging for FN2O according to Foken et al 2004, based on a combination of Steady State and Integral Turbulence Characteristics tests by Foken and Wichura (1996) (i.e., 0, 1, 2)	nondimensional
FNO_SSITC_TEST	Results of the quality flagging for FNO according to Foken et al 2004, based on a combination of Steady State and Integral Turbulence Characteristics tests by Foken and Wichura (1996) (i.e., 0, 1, 2)	nondimensional
FNO2_SSITC_TEST	Results of the quality flagging for FNO2 according to Foken et al 2004, based on a combination of Steady State and Integral Turbulence Characteristics tests by Foken and Wichura (1996) (i.e., 0, 1, 2)	nondimensional
FO3_SSITC_TEST	Results of the quality flagging for FO3 according to Foken et al 2004, based on a combination of Steady State and Integral Turbulence Characteristics tests by Foken and Wichura (1996) (i.e., 0, 1, 2)	nondimensional
H_SSITC_TEST	Results of the quality flagging for H according to Foken et al 2004, based on a combination of Steady State and Integral Turbulence Characteristics tests by Foken and Wichura (1996) (i.e., 0, 1, 2)	nondimensional
LE_SSITC_TEST	Results of the quality flagging for LE according to Foken et al 2004, based on a combination of Steady State and Integral Turbulence Characteristics tests by Foken and Wichura (1996) (i.e., 0, 1, 2)	nondimensional
TAU_SSITC_TEST	Results of the quality flagging for TAU according to Foken et al 2004, based on a combination of Steady State and Integral Turbulence Characteristics tests by Foken and Wichura (1996) (i.e., 0, 1, 2)	nondimensional

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APPENDIX 2 currently operational and historic Eddy Covariance Sites in Africa (Sites highlighted in grey are no longer operational)

	Site	Latitude and Longitude	Measured Ecosystem	Dominant species	Annual NEE Range (g C m^{-2} yr^{-1})	Vegetation Macrogroup	Vegetation subclass	Mean Annual Temp (°C)	Mean Annual Precipitation (mm)	Author
Southern Africa										
1	Dqae Qare, Botswana	21°39'21.21" S 21°49'32.83" E	Savanna	Acacia erioloba, Combretum spp., Terminalia sericea, and Eragrostis pallens and E. lehmaniana	-	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savbanna & Shrubland	-	400	(Williams & Albertson, 2004)
2	Maun, Botswana	19°57'42.98" S 23°33'35.78" E	Mopane woodland	Colospherm um mopane, Terminalia sericea	12*	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland	22	464	(Scanlon & Albertson, 2004; Veenendaal et al., 2004)
3	Okwa River Crossing Botswana	22°24'32.76" S 21°42'47.16" E	Open shrubland with scattered trees	Acacia mellifera Grewia flava	-	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland	-	407	(Scanlon & Albertson, 2004)

	Site	Latitude and Longitude	Measured Ecosystem	Dominant species	Annual NEE Range (g C m^{-2} yr^{-1})	Vegetation Macrogroup	Vegetation subclass	Mean Annual Temp (°C)	Mean Annual Precipitation (mm)	Author
4	Tshane, Botswana	24° 9'50.76"S 21°53'35.16" E	Open savanna	Acacia luederitzii Acacia mellifera	-	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland	-	365	(Scanlon & Albertson, 2004)
5	Guma Lagoon	18°57'53.01" S 22°22'16.20" E	Perennial swamp	Phragmites spp. and Cyperus papyrus	−894.2 ± 127.4*	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.5 Tropical Freshwater Marsh, Wet Meadow & Shrubland			(Helfter et al., 2022)
6	Nxaraga	19°32'53.00" S 23°10'45.00" E	Seasonal swamp	Phragmites spp. and Miscanthus junceus; P. repens, Cynodon dactylon and Sporobolus spicatus.	−1024.5 ± 134.7*	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.5 Tropical Freshwater Marsh, Wet Meadow & Shrubland			(Helfter et al., 2022)
7	Malopeni	23°49'57.14" S 31°12'51.70" E	Mopane savanna	Colosphermum mopane	-	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland	22.2	472	(Dzikiti et al., 2019)

	Site	Latitude and Longitude	Measured Ecosystem	Dominant species	Annual NEE Range (g C m^{-2} yr^{-1})	Vegetation Macrogroup	Vegetation subclass	Mean Annual Temp (°C)	Mean Annual Precipitation (mm)	Author
8	Middleburg Heavy Grazing, South Africa	31°25'48.69" S 25°0'57.70"E	Nama-Karoo	Aristida diffusa, Aristida congesta	-92 ± 66 to 59 ± 46	Temperate & Boreal Grassland and Shrubland (2.B)	2.B.7 Salt Marsh 3.A.2 Warm Desert & Semi-Desert Scrub & Grassland	15	374	(Rybchak et al., 2024)
9	Middleburg Lenient Grazing, South Africa	31°25'20.97" S 25°1'46.38"E	Nama-Karoo	Digitaria eriantha, Pentzia globosa	-90 ± 51 to 84 ± 43	Temperate & Boreal Grassland and Shrubland (2.B)	2.B.7 Salt Marsh 3A2 ????? 3.A.2 Warm Desert & Semi-Desert Scrub & Grassland	15	374	(Rybchak et al., 2024)
10	Mongu, Zambia	15°26'16.80" S 23°15'10.80" E	Woodland	Brachystegia bakeriana, Brachystegia spiciformis	-	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland	24.6	945	(Merbold et al., 2009; Scanlon & Albertson, 2004)

	Site	Latitude and Longitude	Measured Ecosystem	Dominant species	Annual NEE Range (g C m^{-2} yr^{-1})	Vegetation Macrogroup	Vegetation subclass	Mean Annual Temp (°C)	Mean Annual Precipitation (mm)	Author
11	Skukuza, South Africa	25° 1'11.04"S 31°29'48.78" E	Broadleafed and fine-leafed Savanna	Combretum sp. Acacia sp.	-138 to 155	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland	22	547	(Archibald et al., 2009; Khosa et al., 2019; Kutsch et al., 2008; Merbold et al., 2009; Williams & Albertson, 2004)
12	Agincourt South Africa	24°49'15.74" S 31°12'37.43" E				Tropical Forests (1.A)	1.A.2 Tropical Lowland Humid Forest			
13	Welgegund, South Africa	26°34'10.00" S 26°56'21.00" E	Savanna grassland	Thornveld (Eragrostis trichophora, Panicum maximum and Setaria sphacelate)	-85 ± 16 to 139 ± 13	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland	18	540	(Majozi et al., 2021; Räsänen et al., 2017, 2020)

	Site	Latitude and Longitude	Measured Ecosystem	Dominant species	Annual NEE Range (g C m^{-2} yr^{-1})	Vegetation Macrogroup	Vegetation subclass	Mean Annual Temp (°C)	Mean Annual Precipitation (mm)	Author
14	Benfontein Savanna, South Africa	28° 53' 26.16" S 24° 51' 40.03" E	Grassland/ Savanna	V.erioloba, V.tortilis, S. Lancea, S. mellifera; Schmidtia pappophoroides and Stipagrostis uniplumis		Warm Desert & Semi-Desert Woodland, Scrub & Grassland (3.A)	3.A.2 Warm Desert & Semi-Desert Scrub & Grassland	17.8	419	(Maluleke et al., 2024)
15	Benfontein Karoo, South Africa	28°53'26.16" S 24°51'40.02" E	Karoo System	Pentzia globosa		Warm Desert & Semi-Desert Woodland, Scrub & Grassland (3.A)	3.A.2 Warm Desert & Semi-Desert Scrub & Grassland	18	419	(Maluleke et al., 2024)
16	Spioenkop, South Africa	28°42'14.72" S 29°31'34.09" E	Thornveld Grassland	Thornveld, V. karroo, V.sieberiana var woodii and V. nilotica; Themeda triandra and Cymbopogon excavatus		Temperate & Boreal Grassland and Shrubland (2.B)	2.B.2 Temperate Grassland, Meadow & Shrubland	17.3	822	

	Site	Latitude and Longitude	Measured Ecosystem	Dominant species	Annual NEE Range (g C m^{-2} yr^{-1})	Vegetation Macrogroup	Vegetation subclass	Mean Annual Temp (°C)	Mean Annual Precipitation (mm)	Author
17	Cathedral Peak, South Africa	28° 59' 35.58" S 29° 15' 5.60" E	uKhahlamba Basalt Grassland	Bromus speciosus, Pentaschistis tysoniana, Cymbopogon nardus, Festuca caprina		Temperate & Boreal Grassland and Shrubland (2.B)	2.B.2 Temperate Grassland, Meadow & Shrubland	12.8	885	
18	Jonkershoek, South Africa	33° 59' 25.04" S 18° 57' 19.54" E	Boland Granite Fynbos	Protea repens, P. burchelli, P. laurifolia		Temperate & Boreal Grassland and Shrubland (2.B)	2.B.1 Mediterranean Scrub & Grassland	16	1029	
19	Umhlabuyalingana, South Africa	27° 23' 42.72"S 32° 35' 20.04"E	Indian Ocean Coastal Belt Moderate grazing intensity	Dichrostachys cinerea, Psydrax obovata, Strychnos decussata, Hyphaene coriacea		Tropical Forests (1.A)	1.A.1 Tropical Seasonally Dry Forest	22.2	872	
20	Coastal Cashews, South Africa	27°11'60.00" S 32°35'13.00" E	Indian Ocean Coastal Belt heavy grazing	Dichrostachys cinerea, Psydrax obovata, Strychnos decussata, Hyphaene coriacea		Tropical Grassland, Savanna & Shrubland (2.A)	2.A.5 Tropical Freshwater Marsh, Wet Meadow & Shrubland	22.2	872	

	Site	Latitude and Longitude	Measured Ecosystem	Dominant species	Annual NEE Range (g C m^{-2} yr^{-1})	Vegetation Macrogroup	Vegetation subclass	Mean Annual Temp (°C)	Mean Annual Precipitation (mm)	Author
21	Woody encroached Endwell, South Africa	32° 44' 30.76"S 26° 28' 5.80"E	Mesic Escarpment Thicket	Vachellia karroo and Scutia myrtina trees		Temperate & Boreal Grassland and Shrubland (2.B)	2.B.2 Temperate Grassland, Meadow & Shrubland		722	
22	Grassland Endwell, South Africa	32° 44' 56.21"S 26° 28' 22.10"E	Amatole Montane Grassland	Eragrostis plana, Sporobolus fimbriatus, Themeda triandra and Digitaria eriantha		Tropical Forests (1.A)	1.A.1 Tropical Seasonally Dry Forest		722	
23	Vuwani, South Africa	23° 7'48.29"S 30°25'27.52" E	Granite Lowveld savanna			Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland			
24	Agulhas, South Africa	34°44'51.48" S 19°53'25.78" E	Overberg Sandstone Fynbos			Temperate & Boreal Grassland and Shrubland (2.B)	2.B.6 Temperate & Boreal Freshwater Marsh, Wet Meadow & Shrubland			

	Site	Latitude and Longitude	Measured Ecosystem	Dominant species	Annual NEE Range (g C m^{-2} yr^{-1})	Vegetation Macrogroup	Vegetation subclass	Mean Annual Temp (°C)	Mean Annual Precipitation (mm)	Author
Central Africa										
25	Kissoko, Congo Rep	4°44'0.00"S 12° 1'0.00"E	Clonal Eucalyptus plantation	Urograndis (E. urophylla & E. grandis)	-	Tropical Forests (1.A)	1.A.2 Tropical Lowland Humid Forest	23.5	1076	(Merbold et al., 2009)
26	Tchizalamou, Congo Rep	4°17'21.00"S 11°39'23.00" E	Grassland	Loudetia sp., Ctenium newtonii	-	Tropical Forests (1.A)	1.A.2 Tropical Lowland Humid Forest	26	1150	(Merbold et al., 2009)
27	Yangambi DR Congo (CongoFlux)	0°48'52.00"N 24°30'8.90"E	Mixed semi-deciduous moist forest	(Oxystigmo-Scorodophloeion alliance) Scorodophloeus zenkeri, Panda oleosa, Anonidium mannii, Petersianthus macrocarpus, Stautia kamerunensis and Erythrophleum suaveolens species		Tropical Forests (1.A)	1.A.2 Tropical Lowland Humid Forest			
West Africa										

	Site	Latitude and Longitude	Measured Ecosystem	Dominant species	Annual NEE Range (g C m^{-2} yr^{-1})	Vegetation Macrogroup	Vegetation subclass	Mean Annual Temp (°C)	Mean Annual Precipitation (mm)	Author
28	Dangbo 2, Southern Benin	6°36'26.64"N 2°32'34.80"E	Oil Palm plantation	Oil Palm Elaeis guineensis Jacq.		Tropical Forests (1.A)	1.A.4 Tropical Flooded & Swamp Forest	26.8 ±1.4 ℃	1440	Mamadou et al. Ossanatu Poster ICOS 2024
29	Bira	9°49'39.97"N 1°42'56.63"E	former fallow transforming into a shrub savannah			Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland			
30	Bellefoungou, Benin	9°47'24.00"N 1°43'12.00"E	Cleared Protected forest	Isoberlinia spp. and Vitellaria paradoxa	-640 ± 50*	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland	-	1303	(Ago et al., 2016; Hounsinou et al., 2022; Mamadou et al., 2016)
31	Bia Tano Forest Reserve	7° 0'60.00"N 2°37'0.00"W	Natural forest subject to significant LULC changes			Tropical Forests (1.A)	1.A.2 Tropical Lowland Humid Forest			

	Site	Latitude and Longitude	Measured Ecosystem	Dominant species	Annual NEE Range (g C m^{-2} yr^{-1})	Vegetation Macrogroup	Vegetation subclass	Mean Annual Temp (°C)	Mean Annual Precipitation (mm)	Author
32	Nalohou, Benin	9°44'24.00"N 1°36'0.00"E	Cultivated savanna	maize, cassava, yam, beans + some isolated trees (P. biglobosa, D. guineense, Vitellaria paradoxa, Isoberlinia doka, A. guayanus, P. maximum)	-327 to -138*	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland		1190	(Ago et al., 2014)
33	Nangatchori, Benin	9°39'0.00"N 1°44'24.00"E	Degraded woodland	Isoberlinia spp, Monotes kerstingii, Andropogon guayanus	29 ± 16*	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland	-	1254	(Ago et al., 2015)
34	Nazinga Park, Burkina Faso	11° 9'7.20"N 1°35'9.60"W	Sudanian Savanna	Daniellia oliveri, Burkea Africana and Isoberlinia doka	-387 ± 23*	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland	27.1	1028	(Quansah et al., 2015)

	Site	Latitude and Longitude	Measured Ecosystem	Dominant species	Annual NEE Range (g C m^{-2} yr^{-1})	Vegetation Macrogroup	Vegetation subclass	Mean Annual Temp (°C)	Mean Annual Precipitation (mm)	Author
35	Bontioli, Burkina Faso	10°51'56.00" N 3° 4'22.00"W	Grass and shrubland	Andropogon ayanus, Loudetiopsis kerstingii	-429 ± 100 to -179 ± 98	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland	26.1	926	(Brümmer et al., 2008)
36	Cameroon 55m tower in Ntui	4°24'33.4"N 11°37'14.2"E	Cocoa agroforestry	Cacao theobroma, Milicia excelsa, Ceiba pentandra, Terminalia superba		Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland	~25	~2000	
37	Douala	4° 4'12.00"N 9°40'48.00"E	Urban site	N/A			1.A.2 Tropical Lowland Humid Forest			
38	Kayoro Dakorenia, Ghana	10°55'4.80"N 1°19'15.60"W	Mixture of fallow and cropland	Andropogon and Cenchrus; Entada africana, Acacia dudgeoni and Vitellaria paradoxa.	108 ± 6*	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland	-	-	(Quansah et al., 2015)

	Site	Latitude and Longitude	Measured Ecosystem	Dominant species	Annual NEE Range (g C m^{-2} yr^{-1})	Vegetation Macrogroup	Vegetation subclass	Mean Annual Temp (°C)	Mean Annual Precipitation (mm)	Author
39	Sumbrungu, Ghana	10°50'45.60" N 0°58'12.00"W	Short grassland savanna	Brachiaria lata, Chloris piloasa and Cassia mimosoides; Parkia biglobosa, Adansonia and Lannea microcarpa	128 ± 7*	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland	-	375	(Quansah et al., 2015)
40	Kelma, Mali	15°13'12.00" N 1°34'12.00"W	Acacia woodland	Acacia seyal	-309 ± 106	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland	29.6	650 (300 inflow)	(Merbold et al., 2009; Tagesson, Fensholt, et al., 2016)
41	Agoufou, Mali	15°20'24.00" N 1°28'48.00"W	Open woody savanna	Acacia spp., Balanites aegyptiaca, Combretum gluttinosum	-89 ± 31*	Warm Desert & Semi-Desert Woodland, Scrub & Grassland (3.A)	3.A.2 Warm Desert & Semi-Desert Scrub & Grassland	29.7	350	Merbold et al., 2009; Tagesson, Fensholt, et al., 2016)

	Site	Latitude and Longitude	Measured Ecosystem	Dominant species	Annual NEE Range (g C m^{-2} yr^{-1})	Vegetation Macrogroup	Vegetation subclass	Mean Annual Temp (°C)	Mean Annual Precipitation (mm)	Author
42	Hapex, Niger	13°33'0.06"N 2°31'0.02"E	Fallow savanna	Guiera senegalensis, Juss.	-32*	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland			(Hanan et al., 1998)
43	Wankama-Fallow, Niger	13°39'0.00"N 2°37'48.00"E	Fallow bush	Guiera senegalensis, Zornia glochidiata	-137 ± 37 to -107 ± 26	Warm Desert & Semi-Desert Woodland, Scrub & Grassland (3.A)	3.A.2 Warm Desert & Semi-Desert Scrub & Grassland	29.5	560	(Merbold et al., 2009; Tagesson, Fensholt, et al., 2016)
44	Wankama-Millet, Niger	13°38'24.00" N 2°37'48.00"E	Millet crop	Pennisetum glaucum	-63 ± 34 to -10 ± 29	Warm Desert & Semi-Desert Woodland, Scrub & Grassland (3.A)	3.A.2 Warm Desert & Semi-Desert Scrub & Grassland	28.5	560	(Merbold et al., 2009; Tagesson, Fensholt, et al., 2016)

	Site	Latitude and Longitude	Measured Ecosystem	Dominant species	Annual NEE Range (g C m^{-2} yr^{-1})	Vegetation Macrogroup	Vegetation subclass	Mean Annual Temp (°C)	Mean Annual Precipitation (mm)	Author
45	Dahra, Senegal	15°23'60.00" N 15°25'48.00" W	Low tree and shrub savanna	Balanites aegyptiaca, Acacia tortilis and Acacia Senegal; Eragrostis tremula	-244 ± 50 to -166 ± 40	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland	28.9	416	(Tagesson et al., 2015; Tagesson, Fensholt, et al., 2016; Wieckowski et al., 2024)
46	Faidherbia-Flux, Niakhar-Senegal		Agro-Silvo-Pastoral (Agroforestry)	Faidherbia albida (tree) and crops (Pennisetum glaucum (pearl millet) + Arachis hypogea (peanut)	-235 ± 48	Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland	26.49	574 ± 149	(Guzinski et al., 2023; Rahimi et al., 2021; Roupsard et al., 2020)
East Africa										
47	Maktau, Taita Kenya	3°25'32.7"S 38°08'21.5"E	Small agricultural fields	maize, beans, avocados, and grass, with small native or exotic forest stands		Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland	18.5		(Liu et al., 2021)

	Site	Latitude and Longitude	Measured Ecosystem	Dominant species	Annual NEE Range (g C m^{-2} yr^{-1})	Vegetation Macrogroup	Vegetation subclass	Mean Annual Temp (°C)	Mean Annual Precipitation (mm)	Author
48	Choke, Taita Kenya	3°38'44.3"S 38°21'25.9"E	Woodland savanna			Tropical Grassland, Savanna & Shrubland (2.A)	2.A.1 Tropical Lowland Grassland, Savanna & Shrubland			
49	Kapiti, Kenya	1°38'0.60"S 37° 8'29.76"E	Rangeland			Warm Desert & Semi-Desert Woodland, Scrub & Grassland (3.A)	3.A.2 Warm Desert & Semi-Desert Scrub & Grassland			
50	Ausquest, Kenya	1°36'51.1"S 37°07'59.2"E	Farmland			Warm Desert & Semi-Desert Woodland, Scrub & Grassland (3.A)	3.A.2 Warm Desert & Semi-Desert Scrub & Grassland			
51	Demokeya, Sudan	13°16'48.00" N 30°28'48.00" E	Sparse acacia savanna	Acacia savanna (Acacia nilotica, A. tortilis, A. Senegal)	-131 ± 44 to -87 ± 25	Warm Desert & Semi-Desert Woodland, Scrub & Grassland (3.A)	3.A.2 Warm Desert & Semi-Desert Scrub & Grassland	26	320	(Ardö et al., 2008b; Tagesson, Fensholt, et al., 2016)

Appendix 3 Summarised the measurement guidelines for the requirements of measurement parameters for Global Atmosphere Watch stations

Parameters	Site Requirements	Methodologies	Ancillary Requirements
Greenhouse Gases			
CO_2 (ppm) CH_4 (ppb)	Long residence times of gases which allows background concentrations at remote sites and characterisation of sources and sinks (vegetation).	Cavity Ring Down Spectroscopy (CRDS), Non-Dispersive Infrared (NDIR), Gas chromatography-Flame ionisation Detection (GC-FID)	Meteorological measurements (windspeed and wind direction, temperature, dewpoint, atmospheric pressure). QA/QC using internally consistent standard gas calibration scale.

Parameters	Site Requirements	Methodologies	Ancillary Requirements
N_2O (ppb)	They originate from both anthropogenic (fossil fuel combustion, agriculture) and natural (oceans, biomass burning). It has a long atmospheric lifetime (150 years), but local sources can interfere with measurements at regional sites.	Cavity Ring Down Spectroscopy (CRDS), Gas chromatography-Electron Capture Detection (GC-ECD)	Meteorological measurements (windspeed and wind direction, temperature, dewpoint, atmospheric pressure). QA/QC using internally consistent standard gas calibration scale

Ozone (surface)	Ozone is a reactive gas, measurements in many locations are required to define its spatial and temporal variations. Near sources of industrial pollution or biomass burning, ozone concentrations are generally elevated due to photochemical production. At sites more remote from these primarily anthropogenic influences, background measurements may be representative of broad geographic region. The elevation of a site may be an important factor in determining the type of measurement obtained. High variability of tropospheric ozone, many stations are required to adequately determine and assess its global distribution	UV-photometry-based ozone monitors are available from commercial manufacturers. The basic measurement principle is the attenuation of UV light at a wavelength of 254 nm due to the presence of ozone in a flowing air sample	Standard meteorological measurements and a tracer for local pollution such as continuous measurements of CO, NO or aerosol absorption by e.g., aethalometer. QA/QC: Internal inter-comparisons by the station operator with a NIST-traceable ozone calibrator are recommended every 6 months to determine possible instrument malfunction. Periodic inter-comparisons between an instrument maintained as a network standard and the station instrument provides one means of ensuring an instrument's accuracy and making corrections to station instrument records.

Parameters	Site Requirements	Methodologies	Ancillary Requirements
Chlorofluorocarbon (CFC's)			
· CFC-11 (CFCI3) · CFC-12 (CF2CI2) (units of measure: dry mole fraction, ppt)	Long residence times of gases which allows background concentrations at remote sites. Local sources may interfere, and can be used for regional estimates	Gas chromatography (GC), or on site using clean stainless-steel flasks for off-site GC analysis	Meteorological measurements (windspeed and wind direction, temperature, dewpoint, atmospheric pressure). QA/QC using internally consistent standard gas calibration scale.
Ozone			

Total Column Ozone	A major factor in site selection for column ozone is a frequent cloud-free view of the sun throughout the year and low concentration of air pollutants. Appropriate housing for the instrument is essential to minimise temperature fluctuations of the instrument which cause problems in maintaining the extremely high ± 1% measurement accuracy required. It is also essential that trained observers be available daily for frequent measurements whenever the clear sky conditions are present since observations are usually performed with manually operated instruments.	Ground based measurements through different absorption of UV radiation by ozone at different wavelengths (290 and 340nm) can be conducted by 3 major types of instruments: ● Dobson Spectrophotometer ● Brewer Grating Spectrophotometer ● M-124 ozonometer	Clear sky conditions. QA/QC Intercalibration with World Dobson calibration centre.

Parameters	Site Requirements	Methodologies	Ancillary Requirements
Ozonesondes (vertical distributions)	Ozonesondes can be launched from almost any place in the world where the necessary support equipment is available (telemetry to ground based station). Balloons require a source of helium (tanks brought to the site) or hydrogen (provided by a generator at the site). The intercomparison of the sonde integrated column with ground based total column measurements provides a good indication of the quality of the measurements.	Electrochemical concentration cells (ECC sondes) attached to balloon with meteorological measurements	Total column and surface ozone measurements. QA/QC and calibration of sondes.
Reactive Gases			

CO (ppb)	Atmospheric lifetime of CO varies from weeks to months depending on OH concentrations. As a result, there are relatively large differences in CO mixing ratios determined on regional scales. Measurements at established background sites will define geographical distributions and establish growth rates, but additional measurements at sites located closer to major sources (industry, transportation, and biomass burning), and measurements above the planetary boundary layer, are necessary to define postulated global budgets of this gas	Several analytical techniques: • GC-FID or GC with Mercuric Oxide reduction detector. • Gas Filter Correlation Radiometry (GFC) - NDIR • Tuneable Diode Laser Spectroscopy (TDLS)	Meteorological measurements (windspeed and wind direction, temperature, dewpoint, atmospheric pressure). QA/QC using internally consistent standard gas calibration scale.

$SO2$	It is a climatically active trace species, because atmospheric SO_2 reacts photochemically (homogeneous conversion) and on airborne particles (heterogeneous conversion) to produce sulphates. Sources for SO_2 in the atmosphere include the sea, volcanic activity, anthropogenic emissions, and biomass decay processes. Measurements to monitor the background concentration of SO_2 should be made far away from sources. Careful placement of the SO_2 monitoring lines should be considered to reduce contamination from local sources, such as traffic, and heat/power generators. SO_2 is a reactive gas with an atmospheric lifetime of hours to days. It may stick to intake lines or oxidize within water drops condensed in the lines. Thus, intake lines should be made of inert material (Teflon, stainless steel) and be as short as possible.	Measured continuously using either a pulsed-fluorescence analyser or a flame -photometric device	Meteorological measurements (windspeed and wind direction, temperature, dewpoint, atmospheric pressure). QA/QC using internally consistent standard gas calibration scale.

Parameters	Site Requirements	Methodologies	Ancillary Requirements
Aerosol Optical Depth			
AOD	Aerosol sampling equipment should be housed in a shelter that provides a controlled environment (temperature 15-30°C). Sample air should be brought into the instrument housing through a vertical stack with an inlet that is well above ground level. For sites in level terrain, surrounded by no or low vegetation, a height of 5-10 m above ground level is recommended.	The most common instruments are: • sun-photometers or precision filter-radiometers (FR), as their wavelengths are not limited to the visual (photometric) spectral range. WMO recommends three centre wavelengths at 368, 500 and 862 nm, with an optional channel at 412 nm.	The Rayleigh optical depth above the station is required, which can be calculated from the station pressure. Moreover, the 500 nm channel is influenced by ozone, so its column density must be known. A nearby Dobson station may provide the data or some adequate device at the station itself.

Aerosol Lidar	For radiative transfer calculations, altitude-resolved information about aerosols is needed. Ground-based remote sensing by lidar (light detection and ranging) can provide the needed information on vertical aerosol distributions and their variations, as well as information on the presence and vertical distribution of clouds. The integration of an aerosol lidar with measurements by radiosonde, ozonesonde and sunphotometer and with trajectory calculations is the most promising combination	An aerosol backscatter lidar system typically consists of a laser transmitter and an optical receiver in parallel or collinear arrangement.	Molecular backscatter can be calculated from atmospheric pressure and temperature data provided by radiosondes if available. Alternatives are products from a weather forecast model like ECMWF, or surface temperature plus a model atmosphere. • QA/QC: Intercomparison of secondary products (e.g. extinction profiles, optical depth) with • results from integrating systems (e.g. sunphotometers), in situ systems on nearby mountain sites or airborne systems

Parameters	Site Requirements	Methodologies	Ancillary Requirements
Solar Radiation			

Direct Diffuse Total	Surface solar radiation is highly variable in time and space. Siting requirements for solar power utilization may vary from those seeking regional representativeness for climate studies. For solar power utilization the best site will be that at which the power application is to be made or from a site or set of sites near enough that measurements are representative of conditions at the prime site. For climate applications, the site must be free of sub-grid scale influences. The global climate grid scale of interest will depend on the spatial resolution of the diagnostic and analytic tools used in a particular climate study. In general, a solar radiation measurement site will be useful in climate analysis, if free of local influences such as orographic cloud effects, localized moisture or pollution sources. The site must provide a stable platform from which to make the observations and have access for routine instrument inspection and maintenance.	Pyranometers are used for diffuse and reflected irradiance. • Pyrradiometer are used for net radiation. • Pyrheliometers are used for direct irradiance and requires a sun tracking device. • Pyrgeometers for upward and downward directed terrestrial irradiance.	The increasing need for multiple types of data to address environmental problems should encourage those deploying instrumentation to set up the radiation station at locations where meteorological and/or atmospheric chemistry measurements are already routinely obtained. At locations where this is not possible, the measurement of basic meteorological variables (e.g. temperature, pressure, humidity) should be considered the minimum ancillary observations. The measurement of aerosol optical depth (AOD) and ultraviolet (UV) radiation are also considered as complimentary measurements to solar and terrestrial radiation. For more scientific purposes, co-location with upper air sounding stations is useful, especially when UV and aerosol measurements are also made at the same location

UV radiation	Ultraviolet (UV) radiation reaching the Earth's surface is classified into two domains: UV-A (315-400 nm) and UV-B (280-315 nm). UV-A is only slightly affected by ozone, while the steep atmospheric cut-off in the UV-B range (around 290 nm) is caused by the absorption of UV radiation by ozone in the atmosphere. This range is of crucial importance for photo-biological processes inducing several biological damages on living cells and plays a major role in the deterioration of numerous non-biological materials. In addition, UV radiation strongly affects photochemistry, e.g. by the production of OH radicals. In general, the shorter wavelengths in the UV-B region are increasingly more effective and, therefore, variations in ozone will have a strong effect on the surface irradiance	The instrumentation used for UV monitoring at the Earth’s surface comprises four basic classes of UV measuring devices: spectroradiometers, broadband radiometers, filter radiometers and biological dosimeter.	UV data in isolation are of limited use, ancillary measurements are required. Additional information should be provided on background operational details: where, when and how were the measurements made, including instrument characteristics and uncertainty limits

Parameters	Site Requirements	Methodologies	Ancillary Requirements
Meteorological Parameters			

Temperature Windspeed and direction Atmospheric pressure Relative humidity / DewPoint Precipitation	The climatology, along with the topography and ecosystems of a site, must be described and understood to interpret the observations properly. It may be difficult to find a location that will meet all the requirements for measuring all species important to global change. Therefore, as a first step, the global change parameter(s) important for measurement and study within the region of interest should be identified, and then the best site in the region should be located where the most representative measurement of the parameter(s) can be made. If solar fluxes are important, then clear skies are a prerequisite; if CO_2 is important, then sources and sinks around and upwind of the site must be understood and quantified, etc. The climatology of the region must be of sufficient spatial and temporal homogeneity to ensure the broadest extrapolation of the results in both space and time. The influence of local factors such as local wind regimes, orographic rain bands/shadows, dust storms, or seasonal (such as slash and burn) fires must be identified and factored out of the long-term measurements if a broad extrapolation of the data is intended. The same procedure is applicable for infrequent local pollution sources, which must be identified and edited out of the data record.	Temperature wind speed and direction, pressure, relative humidity/dew point, and amount of precipitation are the standard meteorological parameters that should be recorded at GAW stations. Meteorological instrumentation has been standardized around the world. A continuous and in-situ measurement programme of meteorological parameters will be necessary to complement and interpret the individual global change parameters as well as their chemical and dynamical transformations at each regional station. The measurements should be of sufficient frequency and accuracy to register the smallest variations in, and possible long-term increases of, the trace species investigated, to document changes in the Earth-atmosphere system. Automated meteorological stations are highly desirable for these applications	