



Barriers and Lessons of Quantifying Carbon in Africa and Siberia for Climate Change Actions

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ABSTRACT

The study aims to provide a critical overview of the existing evidence on the impacts of climate change on carbon sequestration potential in Asian and African ecosystems, enabling scholars to navigate the field. The study compared recent changes in carbon cycles in the permafrost region and various ecosystems in the African region, highlighting the prospects and challenges, and evaluating the directionality of future research. A total of 37 peer-reviewed publications were evaluated on the following topics: 1. carbon-climate feedback in Siberia and Africa; 2. prospects and challenges of the carbon cycle, and directionality of research. The major finding from this study is that climate change has negatively affected the tundra glacier permafrost ecosystem of the Asian continent, as well as the coastal marine wetlands, grasslands, forests, and farmlands ecosystems in Africa across all sectors of the economy. Africa is faced with the problems of data scarcity, standardization, and validation, while the Siberia region is confronted with process complexity, ecosystem bias, and model–observation mismatches. The need for global comparative frameworks harmonizing methods and data co-production between African and temperate scholars. Based on these findings, there is a need for international collaboration across all regions towards the development of a unified methodology for carbon assessment.

Keywords: carbon-climate feedback, permafrost, African ecosystems, carbon sequestration, climate mitigation, adaptation.

1 INTRODUCTION

The climate change impacts on ecosystem carbon sequestration potential are becoming more complex in dimension than ever, as the observed increase in greenhouse gas emissions has negatively affected the living conditions of humankind globally (Abbass et al., 2022). This is strengthening the severity and frequency of climate extremes, affecting over two-thirds of the African population of about 360 million people (Ayanlade et al., 2022). Several studies have reported severe consequences of complex changes in the biogeochemical cycle on tundra glacier permafrost, coastal marine wetlands, grasslands, forests, and farmland ecosystems, which are the main source of livelihood for many people in Africa and the Siberian region of the Asian continent, respectively (Barnes et al., 2023). The observed changes in the carbon-climate feedbacks have been reported by many studies, and the observed increase in greenhouse gas emissions has intensified in recent years, including prolonged dry spells and heat stress (Okon et al., 2021). Although Africa has the worst scenario, the abnormal changes in the biogeochemical cycle have significantly affected the living patterns of many residents in Africa and Asia, while less research has been carried out in the African region of the world (Idris, Opute, Orimoloye, & Maboeta, 2022). Recent studies have shown that the global net forest carbon sink was about $1.10 \pm 0.80 \text{ Pg C a}^{-1}$, whereas the terrestrial carbon

uptake of $0.70\text{--}0.90 \text{ Pg C a}^{-1}$ was obtained for Africa, and less than $1.6\text{--}1.7 \text{ Pg C a}^{-1}$ was obtained for Asia (Hu et al., 2022). Although several multidisciplinary researchers have focused on the impacts of climate change on ecological sequestration and land–gas carbon exchange, the approaches used and findings on ecosystem carbon storage were different and characterized by uncertainties (Malhi, Kaur, & Kaushik, 2021).

While the commitments to addressing global warming by 2050 have reached a mature stage by the developed countries, the African continent and Asian need to quantify the regional carbon ecosystems balance, through the ecological carbon sequestration (Abbass et al., 2022). Estimating the African and Asian carbon ecosystem balance may help to ascertain the magnitude of the global sinks, as well as redefine ambitions for ecosystem management to control the rate of CO_2 growth (Hu et al., 2022). Therefore, managing the complex and more severe changes in the carbon cycle in tundra glacier permafrost, coastal marine wetlands, grasslands, forest, and farmlands ecological zones ought to be a research priority in African and Asian regions, because the poor residents (mainly smallholder farmers) are already facing hunger and food insecurity (Hicks Pries, McLaren, Vaughn, Treat, & Voigt, 2022).

2 METHODOLOGY

To determine the scope of the literature and research methods, this paper adopted a bibliometric analysis to systematically evaluate the publications on ecosystem carbon sequestration based on climate change. The study aims to use a systematic review to investigate the following research questions (RQ):

RQ1. What are the carbon-climate feedbacks in the Africa and Asia regions?

RQ2. What are the prospects and challenges of carbon dynamics in the carbon cycle?

RQ3. What is the directionality of future research?

The methodology of this study involved three main stages, namely the planning stage, protocol stage, and presentation stage, with a view to collecting evidence relating to changes in carbon, relative to the carbon cycle, the influence of the carbon cycle on climate change, and the research gaps. The planning stage is characterized by searching for the relevant topics in literature through the Google Scholar search engine, organization of data, and metadata. The protocol stage involves the selection of literature through screening and pre-coding in the Microsoft Excel environment to sort out the most relevant literature for this study. The activities in this category include the identification of inclusive criteria and exclusive criteria. The presentation stage includes writing and editing of results, discussion, and conclusion. The rationale behind the choice of this method is to minimize bias and maximize the practical relevance of the review across a broader spectrum of carbon cycle-carbon dynamics and climate change impacts on ecosystems in Africa and Siberia. The literature basis of the review was generated following the Preferred Reporting Items for systematic reviews and meta-analysis (PRISMA) method. The data used herein were obtained from Google Scholar. On October 17, 2025, “climate change*” and “ecosystem carbon sequestration*” were selected as keywords for the search in the Google engine for all literature published between 2000 and 2025.

A total of 115 publications: 78 from Web of Science (WoS), and 27 from Science Direct journals were identified by searching titles, keywords, and abstracts, containing climate change and ecosystem carbon sequestration during the study period. The authors later selected 78 published articles based on their relevance for review, and another 6 published articles were removed before the screening process because they appeared to overlap with other sub-groups of topics as shown in Figure 1. Finally, a total of 72 published articles were screened, and 11 articles were excluded. They were duplicates; an additional 24 publications were excluded because they were not focused on Africa and Siberia. The remaining 37 publications were analyzed.

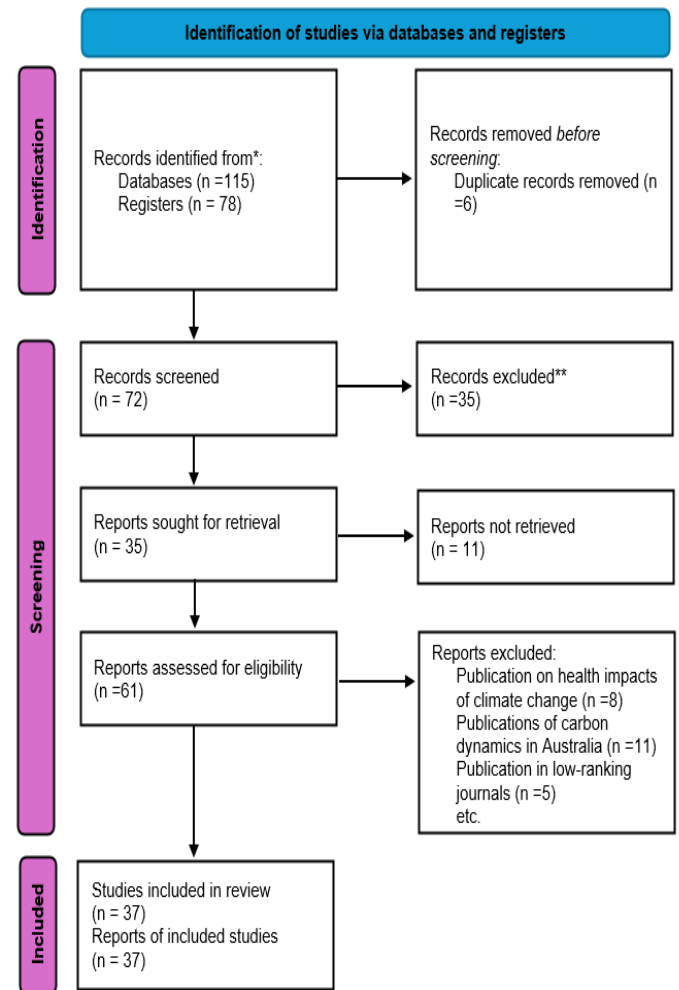


Figure 1: The flow diagram of the study; the studies used for the systematic review process

(Developed from PRISMA 2020: <https://www.prisma-statement.org/>)

3 RESULTS AND DISCUSSION

3.1 CARBON-CLIMATE FEEDBACK: A CASE STUDY OF SIBERIA

The continuous defrosting of permafrost regions is one of the well-known striking evidence of climate change occurring over a wide geographical scale (Timlin, Meyer, Nordström, & Rautio, 2022). Permafrost regions are among the essential pillars of the climate system, without which life on Earth may be difficult or impossible (Mackelprang, Jacobsen, Jansson, & Taş, 2015). This is because the permafrost region not only supports other climate system components but also stores a larger pool of the earth's soil organic carbon, through which some of the major greenhouse gases, which include carbon dioxide and methane, are released into the atmosphere (Liu, Wu, Hu, Wu, & Li, 2021). Soil organic carbon is of two



categories: soil organic carbon formed over millennia (or pre-age soil organic carbon) and recently formed soil organic carbon (or contemporary soil organic carbon) (Lawrence, Harden, Xu, Schulz, & Trumbore, 2015). The challenges confronting humanity in recent times are thawing of the ice in the permafrost regions as a result of global warming, that led to decomposition of these soil organic carbons (Hollesen, Matthiesen, Møller, & Elberling, 2015). The result of the decomposition of soil organic carbon includes flooding of the rivers, sea, or lakes, destruction of lives and properties, and an increase in carbon cycling, which manifests in the increasing release of greenhouse gases into the atmosphere (Nunes, 2023).

The production of greenhouse gases involves the mineralization of soil organic carbon, whereby the ice-soil organic carbon structure begins to defrost, thereby forming thaw, from which dissolved organic carbon and particles of organic carbon are formed (Sjögersten et al., 2016). The process takes place under the influence of carbon fluxes, which primarily provoke the mineralization of the permafrost (X.-Y. Jin et al., 2021). The thawing permafrost in the inland water bodies also begins to emit carbon dioxide and methane into the atmosphere in large quantities, as other important factors influencing the carbon fluxes of the various forms of carbon include age and content of the soil organic carbon, thaw depth, temperature, and seasonal variation (Masyagina & Menyailo, 2020). The amount of thaw releases also depends on the types of the ecosystem, but generally aquatic ecosystems tend to release more forms of carbon than other ecosystem types (Reyes & Loughheed, 2015).

The effects of thaw formation may worsen climate change feedbacks through the increase in the surface and beneath the surface hydrology, increase in the quantities of dissolved organic carbon and particles of organic carbon of the inland water, and increase the concentration of greenhouse gases into the atmosphere (Hayashi, 2013). For instance, the thawing of the permafrost, which occurred in Siberia (Arctic region of the world), has led to the reported incidence of sea level rise, which is accompanied by the large uptakes of dissolved organic carbon and particles of organic carbon (Vonk, 2015). In addition, thawing of permafrost has also contributed to the current increase of the atmospheric methane (CH₄) concentration of >1.87 ppm and the >416 ppm carbon dioxide concentration of the aquatic ecosystem (González-Eguino & Neumann, 2016). The land use, especially urban areas, contributes more to the increase in the soil organic carbon in lakes, rivers, and seas faster than other land uses in different ecosystems (Cheng, Zhang, Shi, & Kung, 2022).

The main challenge is about the rise in the concentration of the anthropogenic methane whose global warming potential far outweighs the carbon dioxide concentration which requires continuous research around the themes: the quantification of emission pathways for pre-age and modern carbons in all forms; rates of mass concentration of thaw lost; factors

responsible for transformation of the soil organic carbon and; the spatial variation of the forms of carbon (Anderson, Hawkins, & Jones, 2016). The year 2022 13th edition of the emission gap report of the United Nations Environment Program (UNEP) states that the global greenhouse gas emissions have continued to increase over the decade at a reduced growth rate of 1.1% compared to about 2.6% more than a decade ago. In the emission gap report, of all the global greenhouse gases (GHGs) emissions, about 75% of the GHGs comes from the G20 members' countries with about 13 tons of CO₂ equivalent (tCO₂e) of the world average per capita, being the second highest after the United States of America. The least developed countries, on the other hand, emit only 2.3 tons of CO₂ equivalent (tCO₂e), notably the non-Arctic regions of the world (Vergara et al., 2013).

Measuring climate feedback involving carbon in its various forms is very important at this critical stage of global warming trends. Fieldwork sampling needs to be carried out to ascertain the representative points of the study area. Laboratory examination of samples should be considered, particularly in carbon dating, for all forms of carbon (Chevalier et al., 2020). Modelling could further help to optimize the spatial extent of the study area better than what the laboratory experiments can do. However, remote sensing and geographic information systems (GIS) should be given a chance to accommodate the spatiotemporal characteristics of the studies and reduce uncertainties in measurement (Hogland & Anderson, 2017). Modeling techniques work more effectively when coupling those measuring instruments (Mari, Wilson, & Maul, 2021). Siberia is an important part of the Asian continent under the Russian Federation, with a land area (which is underlain by permafrost) of about 13.1 million km², and it contains peatlands of extensive carbon stocks. The population of the area as of the 2017 census was 33.77 million, which includes western, eastern, and central Siberia (Isupov & Chernysheva, 2022).

The landscape of Siberia consists of tundra and coniferous vegetation types as well as mountain ranges, which include the Ural, Altai, and Verkhoyansk, and the area is home to the deepest lake in the world, Lake Baikal (Müller et al., 2010). The Siberia region also has the largest Arctic watershed, the Obi River, which is the second largest freshwater contributor to the Arctic Ocean. The study also shows that the Obi River is one of the few Arctic rivers that traverse through all permafrost zones along its course (from permafrost-free to continuous permafrost zone) (Gordeev et al., 2024). Other important features in Siberia include thermoplastic and rivers. The industrial revolution began in the late 1950s, and the region is popular for its contribution to global greenhouse gas (GHGs) emissions and global warming (Yue & Gao, 2018). The study, which will involve passive, active, and carbon neutrality concepts, will therefore be carried out in both Asia and Africa because of its strategic location in the latitudinal belt of the world and hotspots of global climate



change. The passive pipe concept will be applied in this study, which assumes that soil organic carbons are transported from the terrestrial ecosystems to the aquatic ecosystems. The passive pipe concept also assumes the aquatic ecosystems as an isolated ecosystem on which terrestrial landscape studies should be ignored (Fmsa, Cammeraat, & Kuhn, 2014). In this perspective, carbons are transported from land to sea, rivers, or lakes, while on the other hand, carbon neutrality on the other hand assumes zero net emission of carbon (Gabrielli et al., 2023).

The passive pipe concept contributed to the understanding of the traditional carbon cycle before the further development of the increasing carbon cycle as we have it today, in the consolidation of biogeochemical cycle knowledge. However, more than three decades ago, the idea that the inland waters are conduits for the transport of carbon from land to sea began to fade out with the conceptualization of how the inland waters are being affected by external constraints. This idea is termed the active pipe concept (Drake, Raymond, & Spencer, 2017). This recent concept observed that the carbon emission that occurs in aquatic ecosystems is mainly released by terrestrial ecosystems. In the past, scholars believed that carbon leaked from terrestrial ecosystems to the aquatic ecosystem through strong biological productivity, gas fluxes, and hydrological connectivity (Hastie, Lauerwald, Ciais, & Regnier, 2019). The studies were able to identify surface runoff, groundwater drainage, and land flooding as major sources of carbon for aquatic ecosystems. The concept is characterized by the potential for capturing carbon dioxide from the atmosphere, direct transfer of mineral and organic matter to the water bodies, high respiratory rate at the subsurface of rivers, and relatively slow gaseous exchange rates at the water–air interface (Abril & Borges, 2019). The organic carbon and dissolved carbon dioxide formed in the water bodies were derived through the absorption of the atmospheric carbon by the phytoplankton to the inland waters. However, the major drawback of this idea is that this idea may not work without careful consideration of the working effectiveness of vertical and horizontal carbon fluxes (Koehler, Landelius, Weyhenmeyer, Machida, & Tranvik, 2014).

The active concept proposes that the carbon fluxes within the ecosystems are impacted by the metabolic and physical processes that are taking place in each ecosystem (Gattuso, Frankignoulle, & Wollast, 1998). This implies that atmospheric carbon fluxes along the terrestrial, floodable, and aquatic water sources should be adequately conceptualized in two dimensions without underestimating the important contributions of hydrological net export terms in use (Abril & Borges, 2019). The active concept also proposes that inland water should be defined as derivatives of three terms, namely, carbon dioxide flux intensities from the water–air gradient of the partial pressure of carbon dioxide, gas transfer velocity at the water–air interface, and scaled to the surface area of lakes and rivers. Unfortunately,

this perspective is limited by the uncertainties and lack of adequate data coverage (McGillis et al., 2001). The terrestrial perspective, on the other hand, proposes that the terrestrial ecosystem loses a significant part of its residual carbon flux budgets to the aquatic ecosystems. However, studies have noted that flooding may be a limiting factor, particularly in a well-drained area (Jonsson et al., 2007). Irrespective of this disadvantage, the active pipe concept works through the mechanical runoff of the soil surface that facilitates the mobilization of dissolved organic carbons, particles organic carbons, and inorganic carbons in the water bodies (Fei et al., 2019). The wetland perspective noted that the wetland is a rich and efficient source of carbon in all forms, irrespective of its relatively smaller size (10% of the land surface); however, it is presently difficult to quantify the hydrological carbon exports of the wetland due to the scarcity of data (Alikhani, Nummi, & Ojala, 2021). Conclusively, the active pipe concept for inland waters shows that terrestrial ecosystems divert a substantial amount of carbon to the atmosphere and to the sediment sink at the subsurface of the aquatic ecosystems (B. Zhang, Zhao, & Hallett, 2004).

3.2 CARBON-CLIMATE FEEDBACK IN AFRICA

The African perspective highlighted how ecological sequestration and land–gas carbon exchange are affected by climate change, and the focus of the study was on coastal marine wetlands, grasslands, forests, and farmland ecosystems, which are important carbon sinks and play significant roles in climate change mitigation. (Prajapati et al., 2023) Anthropogenic activities, particularly rain-fed agriculture, which account for approximately three-fifths of the economic livelihood, decrease the water-saturated anaerobic soils that store roughly between 45 % and 70 % of all the terrestrial carbon (Khangura, Ferris, Wagg, & Bowyer, 2023). Wetlands, grasslands, forests, and farmlands are ecosystems such as a carbon sink, receiving a significant quantity of carbon, absorbed and sequestered by the ocean ecosystem (blue carbon source) through the biogeochemical cycle. However, the ability to establish the specific blue carbon sources constitutes a major challenge in Africa due to inadequate research, and reducing uncertainties in carbon sequestration and climate change mitigation is one of the most urgent and effective means for reducing climate change risk in Africa (Zhu & Yan, 2022). Interestingly, the development of models and remote sensing technologies has shown that despite our understanding of the carbon–climate feedbacks in Africa, the carbon sink sources remain less researched (Patience, 2021).

Moreover, studies have shown that water resources constitute a major factor influencing the conversion of cropland to forest ecosystems, while converting forest to agricultural ecosystems may lead to a reduction of soil organic carbon stock by between 20 % and 50 % (Mayer et al., 2020). Because of the above finding, the climate change impacts on ecosystem carbon sequestration potential have attracted the



attention of researchers across different disciplines in Africa (Filho et al., 2021). Several studies on climate change have focused on climate change impacts/risks and their effects on natural and human systems, but the present studies have reported that the increasing concentration of greenhouse gases far outnumbered the carbon sequestration and climate change mitigation options available in Africa (Malhi et al., 2021). The carbon sequestration and climate change mitigation options are influenced by the level of education, financial status, and years of farming of people, which in turn are significantly related. The major evidence from the literature is that a significant amount of research focusing on the development of carbon sequestration potential suitable for people in Africa is highly needed (Lipper, Dutilly-Diane, & McCarthy, 2010). The achievement of neutralized carbon by 2050 depends on collective efforts by both the policy makers, independent scholars, and private organizations, and such policies should be rights-based in its approaches in order to avoid maladaptation (Eriksen et al., 2021).

3.3 SOME PROSPECTS AND CHALLENGES

Unlike in the past when the relationships existing between the aquatic ecosystems cycle, and the terrestrial landscapes were not clear, recent development has been able to clearly verify the extricate links among them, which vary over time and space (Mayfield et al., 2021). The active pipe concept has brought about changes in historical records of events in different ecosystems, including relative changes that have occurred as a result of human activities (Van Dover, 2014). Apart from being a confined and reactive ecosystem, the ecological effects of the inland water concept may provide important links for terrestrial ecosystems on certain occasions when certain terrestrial consumers have to be subsidized (Strayer & Findlay, 2010). The emerging issue in this contemporary time is that there were no meaningful efforts at testing the hypothesis that inland waters significantly influence atmospheric carbon dioxide and methane (Tranvik, Cole, & Prairie, 2018). This study has further provided clarifications, and the rates of sedimentation of dissolved organic carbons from terrestrial ecosystems are considerably higher in the aquatic ecosystems, which are also rich in allochthonous carbons (Wild, 2022). Additionally, in lakes respiratory rates of carbon dioxide and methane depend on the connectivity of the inland water with different terrestrial ecosystems at the regional, continental, and global scales (Ferreira, Dodds, & Cunha, 2023). The challenges under here include the existing controversies involving reconciling opinions concerning the roles of intrinsic and extrinsic sources of carbon dioxide emissions, and the emission of carbon dioxide as a result of photochemical reactions in the inland waters (Wasswa, Driscoll, & Zeng, 2022). Such factors depend on wavelength-dependent photochemical reactivity of dissolved organic carbons, wavelength-specific attenuation of light in the water column, and the intensity and spectrum of incoming solar radiation. However, the challenges of mineralization of the organic

matter include errors encountered during the laboratory experiments and the mathematical analysis of findings (Vähätalo, Salkinoja-Salonen, Taalas, & Salonen, 2000). There is a need to integrate different techniques to reduce uncertainties. The study also shows that variation exists both within and between aquatic ecosystems in terms of how food web organization plays a pivotal role in the regulation of aquatic ecosystems as both emission sources and sinks of carbon dioxide in the atmosphere (Matveev & Robson, 2014). While the existing studies have focused attention on the importance of allochthonous carbons in the biogeochemical cycle, few studies have focused on the quantification of the exchange of carbon dioxide and methane between the aquatic ecosystems and the atmosphere (Gustafsson, Deutsch, Gustafsson, Humborg, & Mörrth, 2014). Furthermore, there were negligible studies that paid attention to the spatial pattern of variation between water–atmosphere exchanges at different aquatic ecosystems. Vigorous research is therefore needed to examine the spatial patterns of variation of the water–atmosphere exchanges within the food web configurations (Cui, Xiao, Yang, Hu, & Zheng, 2024).

Scholars have noted that although a substantial amount of carbon dioxide and methane is emitted from inland waters, a significant quantity that is also diverted into the geosphere has been mostly overlooked. This has contributed to a reduction in the accuracy of the allochthonous carbon results using statistical extrapolation, as their choices of measurement technique (Malyan et al., 2022). This has suggested the need to carefully consider carbon stores and carbon fluxes in the present studies with a view to avoiding the existing mistakes made by the previous studies. Interestingly, remote sensing and geographic information systems have been developed to address the identified errors and improve accuracy (Issa, Dahy, Ksikisi, & Saleous, 2020). The integration of modelling techniques with other scientific methods, such as carbon isotopes dating, and modelling will further increase accuracy in this study, and the development of eddy covariance has been highly effective in the quantification of carbon–climate change feedbacks (Baldocchi, 2003).

In the past, continuous efforts have been made to understand the carbon cycle. Surprisingly, when certain findings had been made, further problems were discovered about the carbon cycle (Isson et al., 2020). The stages of research development can be classified into two, namely, the traditional stage, which was characterized by viewing the carbon cycle in an inland water as a closed system, highly affected by carbon imports, and also viewing inland water as a terrestrial ecosystem sink and source of carbon (Biddanda, 2017). The latest stage of research development is the understanding that inland waters as one of the largest sinks and sources of soil organic carbon at the global scale, while the earlier definition assumes a microcosm view of the carbon cycle, the latest approach believes in the



interconnection of the aquatic ecosystems with the global landscapes (Regnier, Resplandy, Najjar, & Ciais, 2022). Understanding inland waters as one of the largest sinks and sources of soil organic carbon at the global scale agrees with the climate system concept of interconnections between the components of the earth, which include the anthropogenic influences by man (Gao et al., 2020). Recently, studies were carried out to investigate quantities of the pre-aged and contemporary carbons, the rates of losses of carbon, carbon fluxes, and the spatial variation in the carbon in its various forms (X. Wang, Haiqing, Li, Song, & Wu, 2012).

The analysis of research findings over a decade now has shown that the amount of carbon dioxide and methane emitted into the atmosphere through the inland water is directly dependent on the proportional quantity of soil organic carbon-rich thaw (Oertel, Matschullat, Zurba, Zimmermann, & Erasmi, 2016). The increase in the concentration of atmospheric carbon dioxide and methane is attributed to the contemporary carbon in the inland water. In contrast, recent studies have shown that the old could also contain a large proportion of soil organic carbons through the actions of the soil microorganisms in the inland waters (Jiang et al., 2020). Several studies have identified eutrophication and urban loads of soil organic carbon as factors contributing to the increase in the quantities of carbon dioxide and methane. Other studies pointed out the reduction of the surface area of the inland water, as well as localizing vegetation, moisture ice content among the constraints to the formation of thaw in the inland waters (Heyang et al., 2021). However, studies have observed a scarcity of studies that pointed out the temporal extent of the quantities of soil organic carbon in an aquatic ecosystem for the carbon cycle (Li et al., 2023).

For example, the global organic carbon stock present in sedimentary rocks is estimated at 15,000,000 Pg of organic carbon. This accounts for more than 99% of the organic carbons contained in other ecosystems combined (Kroeger, Di Primio, & Horsfield, 2011). The organic matrix contained in the sedimentary rocks is made up of approximately 95% kerogen, which is an old (> 50,000 ybp) insoluble, macromolecular organic substance composed of long chains of polymethylenic carbon and aromatic rings (a highly stable compound) (Guillemette, Bianchi, & Spencer, 2017). Therefore, the emission of carbon to the atmosphere by this substrate marks an important stage in the global biogeochemical cycle. While past studies have analyzed the conversion of kerogen from the sedimentary rocks to the atmospheric carbon gases, the influence of microorganisms in achieving oxidation of the kerogen was largely neglected (Cornelissen et al., 2005). Studies have noted the important contribution of biological assimilation of old organic carbon into the inland waters; unfortunately, the studies are scanty in this area of research (Brett et al., 2017). nonetheless, several studies have underscored the influence of

microorganisms in the assimilation of old carbon in more detail (Bruun, Jensen, & Jensen, 2008).

Unperturbed soil naturally accumulates and sequester naturally accumulate and sequester organic carbons at a rate of 33 g C m⁻² yr⁻¹ at a rate of 33 g C m⁻² yr⁻¹ which almost doubles the amount of carbons present in the atmosphere, however, recent studies have shown that the age of the old organic carbon may contain either dissolved carbons or particles organic carbons or both irrespective of the sizes of an area depending on leach ability of soil and precipitation events (Post & Kwon, 2008). Research has shown that old dissolved carbons and particles, organic carbon pools, may be used as an export baseline for the transport of organic carbons to the aquatic ecosystems because their composition consists of fractions of ancient carbons (St. Pierre et al., 2020). Permafrost soil, which is the soil that has remained frozen for at least, minimum of two consecutive years before it begins to undergo thawing, while the relatively large quantities of organic carbon found in the permafrost regions represent one of the most significant carbon sinks (Hicks Pries, Schuur, & Crummer, 2013). Studies have shown that an increase in the air temperature to between 4 °C–78 °C in the Arctic regions could trigger mobilization of a large amount of old frozen organic carbon stock over the next 100 years (Descals et al., 2022).

Although evidence has shown the importance of old organic carbons exported from glacier ecosystems, the extent to which these ancient, glacier-derived organic carbons moved bottom-up of the aquatic food webs requires urgent attention (Fellman et al., 2015). Glaciers and Ice sheets also exhibit similar characteristics as soil permafrost; however, glaciers and Ice sheets are highly associated with the occurrence of sea level rise (Fyke, Sergienko, Löfverström, Price, & Lenaerts, 2018). Recent findings have shown that out of the 6 Pg of organic carbons locked in glaciers and ice-sheets, dissolved organic carbons constitute approximately 48 Tg, which is forecasted to be completely thawed to the inland waters by 2050 (H. Jin & Ma, 2021). In addition, unlike the permafrost soil, which originated through the natural storage imprisoned in the permafrost soil. glacier and ice sheets emanated through the atmospheric transport and deposition of biomass and fossil fuel combustion by-products (Andrews, Jacobson, Osburn, & Flynn, 2018).

Few studies have analyzed the immediate effects of anthropogenic activities, such as urbanization and agriculture, on the transport of old organic carbons in aquatic ecosystems (Häder et al., 2020). Therefore, there is a need to investigate the direct effects of urbanization and agriculture on the age of organic carbons that empties into the aquatic ecosystems, together with the potential utilization by the microorganisms in the inland waters (Cantonati et al., 2020). Reservoir effects constitute one of the serious constraints to assessing the age of aquatic organisms, which often involve the mobilization of carbon atoms within an aquatic ecosystem over a longer time (Q.-Y. Zhang, Ke, Gui, &



Zhao, 2022). This implies transfer of the aged carbon from another reservoir, which results in the depletion in 14 °C activity of the carbon pool present (Bryan, Marchitto, & Lehman, 2010).

3.4 DIRECTIONALITY FOR FURTHER RESEARCH

Although assessing changes in carbon through a biogeochemical cycle is highly challenging in Africa, recent insights drawn from remote sensing, numerical modeling, and regional laboratory initiatives across the region may gradually improve our understanding of the diversity of drivers of biogeochemical cycles and feedback across the region (Cole, Hararuk, & Solomon, 2021). Given the growing momentum of the planned decarbonization policy, which requires scaling up the capacity for biogeochemical cycle assessment, there is a need to consider the drivers and intersectional dynamics of the carbon cycle into the existing diverse and heterogeneous methodologies for assessing changes in carbon through the carbon cycle (Galeazzi, Steinbuks, & Anadon, 2024). This may necessarily include the incorporation of a process-based carbon model that is validated with African data, as well as remote sensing and big data satellite products with ground observation for integrated nutrients detection, which are despite their capacity to deliver data-sharing networks, are still lacking recognition in climate change studies. Analysis at such an integrated spatial scale may certainly help to reduce uncertainties attributed to the existing poor model calibration and inadequate long-term soil carbon and nutrient data in Africa (Srinet et al., 2023). Such a limitation will further help to bridge the poor understanding of the rate of decomposition of carbon under varied climatic conditions. In fact, the growing evidence of a lack of long-term data and carbon monitoring sites pointed out the urgent need for substantially greater development of soil observatories, as well as isotopic and microbial approaches for the quantification of carbon. On the other hand, the methods of assessing carbon in the permafrost region are simpler as the drivers and intersectional dynamics of carbon cycle assessment are factored into the existing heterogeneous methodologies (Yang et al., 2025). Although the permafrost region has a dense network that measures croplands and forest resources, the underrepresentation of urban landscape, peatland, and transitional ecosystems constitutes the major research gap. Because of this deficiency, many scholars believed that the expansion of flux networks that will incorporate diverse land use classes and transitional regimes may help to reduce biases in other important parameters, including the topsoil layers, but the research on the uncertainty in the mechanisms in subsoil carbon stabilization ought to be a top-notch research priority (H.-J. Jin, Wu, & Romanovsky, 2021). Such future research must consider the extension of the depth of the sample and involve radiocarbon and enzyme-based analyses.

To increase the analytical laboratories and personnel for long-term observation, the regional laboratories need to be strengthened, including training and an increase in data-sharing networks. For example, the development of integrated, observation-based biogeochemical assessment networks such as Afriflux may facilitate the collation of scientific results and meta-analysis that link qualitative and quantitative assessments of communities, regions, or nations together at differing biogeochemical processes. Lack of specific process-based evaluation metrics in Africa is currently hampering the directionality of the biogeochemical cycles and their overall effects on climate change (Chai et al., 2020). Thus, there is an urgent need for the African region to address the qualitative and quantitative assessments research gap identified above, but with the inclusion of longitudinal methodology, such that further analysis may be capable of addressing the projected long-term data gaps associated with extreme events (Tambo et al., 2023). However, despite the extensive remote sensing data on soil characteristics in the Arctic region, the soil nutrients data are underused in the literature, and limited cross-scale validation of the advanced model. There is an urgent need to focus future research on nutrient flux inference from optical data and to address the difficulties in scaling from plots to landscapes (J. Wang et al., 2023).

4 CONCLUSION

The key findings from the literature reviewed in this study are that climate change has negatively affected the tundra glacier permafrost ecosystem of the Asian continent, as well as the coastal marine wetlands, grasslands, forests, and farmlands ecosystems in Africa across all sectors of the economy (Cruz et al., 2007). Africa is faced with the problems of data scarcity, standardization, and validation, while the Siberia region is confronted with process complexity, ecosystem bias, and model–observation mismatches. The need for global comparative frameworks harmonizing methods and data co-production between African and temperate scholars. Based on these findings, there is a need for international collaboration across all regions towards the development of a unified methodology for carbon assessment.

Although currently there is no precise estimate of the carbon sink and carbon-climate feedback in the African ecosystems, there is convincing evidence to suggest that a significant amount of research focusing on the development of carbon sequestration potential suitable for people in Africa is highly needed because of the climate-dependent nature of human activities in the region. Systems (Glenday, 2006). Agriculture is the major occupation in Sub-Saharan African countries, and farming makes them more vulnerable to climate change (Connolly-Boutin & Smit, 2016). The result of the study also showed that while the carbon sequestration potential in the Asian ecosystems may be promising within the Paris agreement target, the climate change control in the African



ecosystems may be difficult because large uncertainties in the actual estimate of the carbon - climate feedbacks, and inadequate information about the climate feedbacks and responses may trigger more extreme events in the future in Africa (Jat et al., 2022).

Despite that, UHI projections are well recognized, but a lack of spatial resolution to capture extreme microscale variation in temperature exposure within the urban settings, driven by complex urban morphology, vegetation, and infrastructure, constitutes a major limitation. Therefore, application of very high resolution (<100 m) urban climate models, coupled with detailed population distribution data for the fine-scale intra-urban heat exposure disparities, should be given urgent research priority (Diem, Nguyen et al. 2024). Current mosquito risk exposure projection strongly relies on SSP population grids, whereas there are uncertainties in the validity of such predictions over the regions being affected by extreme future events. Despite the significant climate-driven migration away from the affected regions that often occurs, such a factor is not often dynamically considered in most models (Gorris, Bartlow et al. 2024). Thus, research integrating dynamic models of climate migration feedback into population projection for high-temperature projection regions should be given immediate attention. Although short-term acclimatization to heatwaves is well-documented in the literature, the long-term human physiological adaptation to suppressive extreme events over decades, especially among vulnerable populations in Africa, is poorly understood. Investigating the long-term adaptive capacity and potential thresholds for different populations under chronic climate scenarios should therefore be a leading research priority.

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