Jordan Journal of Agricultural Sciences, Volume **21**, No.**2** **2025**
DOI :https://doi.org/10.35516/jjas.v21i2.2588

Assessing Soil and Subsurface Carbon Sequestration: A Quantitative Analysis

Collins O Molua [1] *

[1] Physics Department, University of Delta, Agbor Delta, Nigeria

Received on 24/4/2024 and Accepted for Publication on 25/12/2025.

ABSTRACT

This study examined the feasibility of using two geographical features: magnetic vessel science and gravimetry, and monitoring the amount of carbon adsorbed in soil and subsurface layers. For the purpose of our study, we conducted field campaigns at various locations where we collected magnetotelluric gravity data by using of specialized equipment and integrated it with geological and environmental data analyses. Magnetotellurics measurements of soil electrical resistivity show a strong negative correlation with organic carbon concentration (e.g., S010 in situ has an electrical resistivity of 82.671 Ωm and organic carbon content of 3,786%). This made it possible to estimate the amount of carbon stored in the soil. Gravimetric changes below the ground were linked to higher levels of CO2 saturation (for example, site G003 had a 0.912 mGal change and a 25.621% CO2 saturation), which helped scientists figure out what kind of carbon storage reservoirs might be there. Using autoregressive integrated moving average (ARIMA) models and nonlinear regression techniques (Levenberg-Marquardt algorithm), time series analyses showed that it was possible to track the dynamics of CO2 injection (gravimetric anomalies went from 0.000 to 1.756 mGal when 0.623 Mt of CO2 was injected) and CO2 plume migration (resistivity went from 35.671 to 7.789 Ω•m as the plume spread to 2.16 km^2). The findings contribute to developing effective climate change mitigation strategies, promoting sustainable land management practices, and informing carbon capture and storage initiatives.

Keywords: carbon sequestration, magnetotellurics, gravity, soil organic geophysical techniques, climate change mitigation

INTRODUCTION

Carbon sequestration, the process of capturing and storing atmospheric carbon dioxide (CO2) in terrestrial and marine ecosystems, as carbon capture and storage are not yet effective enough, is one of the key strategies for mitigating climate change impacts and their widespread repercussions in recent years. While the soils and underground levels are just a spot among the numerous carbon reservoirs, they can make a big difference in storing and sequestering huge amounts of carbon dioxide emissions (Adamu *et al*, 2021). It is of utmost significance to quantify and monitor the carbon stockpile in these habitats not only because the concept itself provides valuable information on the carbon cycle but also because it can help inform climate adaptation and mitigation and increase sustainability in the management of land use.

Indeed, the revelation of how the soil and subsurface layers play critical roles in carbon sequestration is fundamental. Meanwhile, soils harbor the essence of the largest carbon reservoir on the planet, with an estimated amount of 2,500 gigatons of carbon being stored there, more than three times greater than the amount of carbon present in the atmosphere (Reddy *et al*, 2021; Tifafi *et al*, 2018). The huge potential for carbon storage in soils cannot be underestimated since it controls the CO2 level

* Corresponding author. E-mail : collins.molua@unidel.edu.ng

in the air and, subsequently, combats climate change. Through enhancing our grasp of carbon dynamics in these ecosystems, we'll be able to come up with mitigation strategies intended to improve soil carbon sequestration, thus minimizing the release of greenhouse gases into the environment and, as a result, combating the changes brought about by climate change.

Moreover, the aspect of quantifying carbon accumulation within subterranean layers like sedimentary rocks and aquifers is also primarily essential. However, these geological features have been found to have the capacity to hold enormous amounts of carbon for a very long time, resulting in extended carbon sinks. Discovering the carbon load in these subsurface layers gives a clue as to whether CCS is a workable technology and to what extent it can bring about the desired results. CCS solutions attempt to separate CO2 from the factories and then put it where the CO2 is needed to be stored in geological formations (Raza *et al*, 2019; Alcalde *et al*, 2018). This research not only has the potential to find a solution to climate change, but it also has a broader impact that includes reducing climate change. Through improving our knowledge of carbon flows in terrestrial scenarios, we will identify long-lasting methods of soil care, boost agricultural productivity, and enhance ecosystem services. Quantifying the sides of carbon stores under the earth's crust and CO2 using and CO2 storing technologies are the strategies that are supported by the International Energy Agency in the fight for more clean energy production for the steel industry, power plants, and cement producers.

In practice, this research helps not only to expand our basic knowledge about the complex interrelationship between the biosphere, lithosphere, and atmosphere but also to improve environmental forecasting and engineering. It throws light on the biogeochemical processes, which are the major systems of absorbing, transforming, and releasing carbon. Through the application of advanced geophysical methods, including magnetotellurics and gravimetry, this research enhances existing models to enable more accurate carbon dynamics predictions, essential for climate change mitigation strategies and policy decisions. Conventional means are in place for measuring carbon sequestration through examples of soil sampling, but laboratory analysis is normally time-consuming, labor-intensive, and narrowly focused. Remotely-sensible methods and modeling constitute a non-invasive and efficient strategy to characterize subsurface properties and measure changes over time, hence offering an excellent picture of carbon storage dynamics at larger scales (Nayak *et al*, 2019; Heikkinen *et al*, 2020).

In conclusion, the task of sequestration on soils and substrata quantification is of utmost importance before the climate change challenge is mitigated. The findings of this research can be utilized by various policy and decision-makers to craft climate change mitigation techniques, support sustainable land management approaches, and create frameworks for carbon capture and sequestration. Theoretically, it contributes to our fundamental understanding of biogeochemical processes and carbon cycling, while also addressing a significant gap in the literature by employing innovative geophysical techniques for carbon quantification and monitoring.

Purpose Statement

The main objective of this study is to investigate the feasibility of geophysics, particularly magnetotelluric and gravity techniques, for determining the quantity and detecting the changes in carbon storage in topsoil and underlying lithosphere. The study also aims to overcome the drawbacks of conventional soil sampling and laboratory analyses, which can be in terms of places covered and resources used, since they are based on narrow locations and laborious processes. Subsequently, the study is guided by the following objectives: To assess the potential of magnetic telluric gravity methods for quantifying carbon sequestration in soil and subsurface layers at different spatial scales. The development of methods for interpreting and integrating magnetic cross-body and gravimetry data with existing knowledge of biogeochemical processes and carbon dynamics in the terrestrial environment. To investigate the relationship between electrical resistivity and density changes measured by magnetic dilution and gravimetry, respectively, as well as the presence and distribution of carbon-rich materials in soil and subsurface layers. We aim to use these geophysical techniques to track the long-term evolution of carbon storage in terrestrial environments, observing changes in carbon storage and the potential for sequestered carbon, such as relocation or movement. To contribute to the development of effective strategies to mitigate climate change by providing a comprehensive understanding of the carbon cycle and insights into carbon storage in soils and subsurface aquifers on a larger scale.

Literature Review and Gap

Multi-faceted studies across terrestrial ecosystems have used different methods and techniques to assess carbon incorporation into living organisms. The literature is already available and has uncovered a void that has to be filled by putting into use geophysical approaches geared towards stock calculation, monitoring of carbon, and storage of soil and sub-surface layers on a larger scale. The main tools employed were the standard assessments, which incorporate field samples and lab analyses to calculate soil C content and disclose carbon dynamics (Thoumazeau *et al*, 2020; Liu *et al*, 2019). These methods are useful, but their possibilities are also restricted due to sketchy coverage in space, tediousness, and the tendency to be resource-intensive, which makes it quite difficult to monitor carbon sequestration over wide areas and for long periods.

Remote sensing methods include satellite remote observation and airborne LiDAR (Light Detection and Ranging), which can be used to determine the above-ground biomass levels as well as the land cover, a proxy for carbon sequestration as well (Asner *et al.,* 2010; Baccini *et al.,* 2012). Nevertheless, these procedures draw attention to the up-situation carbon pools and do not directly measure the carbon stored in the soil and the subsurface. A high number of areas, including mining exploration, hydrogeology, and mapping geological structures, have already embraced geophysical methods like magnetotellurics and gravity techniques (Zhang & Li, 2019; Zhang *et al.,* 2023). These strategies utilize the underlying course of the subsurface, which includes the electrical resistivity variation and density variations, to distinguish the boundaries and properties that are in that particular place. Nevertheless, we will see that their use for assessing soil and below-surface carbon sequestration is yet another new concept.

Previous studies

While geophysical methods used to quantify carbon are relatively new, many pioneering studies have demonstrated their potential in related fields. For example, researchers used magnetotelluric analysis to detect and characterize underground CO2 plumes in geological formations inside, and thus carbon capture storage technologies. The development was supported (Xu *et al.,* 2019; Fawad &Mondol, 2021). Likewise, researchers have used gravimetric techniques to monitor surface water movements in geologic formations, such as CO2 injection and migration (Torr *et al.,* 2019; Morell *et al.,* 2020). These studies show the potential that gravimetry methods have to detect density changes associated with subsurface carbon storage. However, the direct application of these geophysical techniques to estimate the amount of carbon leached in soils and the subsurface, especially in terrestrial environments, is still largely unexplored. This study aims to evaluate the potential of magnetic tellurics and gravimetry in measuring and tracking carbon formation or storage in these areas. It would help to learn more about curbing climate change.

Theoretical Framework

The theoretical framework of biogeochemical cycling and the methods of geophysical techniques for the subsurface characterization form the basis of this research. The biogeochemical cycling of carbon is an indisputable process that regulates the carbon exchange between diverse reservoirs on Earth, such as the atmosphere, biosphere, and lithosphere. Knowing the methods and processes by which biomass becomes carbon and its subsequent migration to subsoil and surface layers is fundamental for finding the balance on the Earth and for climate change-proofing.

With it, geophysical techniques such as magnetotellurics and gravimetry are driven by the ideas of electromagnetic induction and gravitational field variation, respectively. Telling magnetics relies on the phenomenon of the change in electromagnetic field intensity induced by the Earth to measure the electric resistivity of subsurface layers. The level of carbon present within the sub-surface or changes in these qualities from carbon sequestration operations could influence the electric potential of the subsurface. On the other hand, gravimetry is responsible for the detection of the Earth's gravitational field's small variation, which is a result of density changes resulting from carbon aggregation in the subsurface. This study is hypothesized to be the first step towards developing a complete framework for measuring and overseeing the potential for carbon storage on Earth using large-area noninvasive methods by coupling these geophysical principles with the know-how on biogeochemical cycling and carbon sequestration processes.

Methodology

This study applied a quantitative research strategy that combines field observations, geospatial data acquisition, and data processing. We have employed magnetotellurics and gravimetry as the two geophysical methods of the examination to track carbon sequestration in the soil by both surface and deep layers of the earth within several different study sites. We purposefully designed study sites to suit various geological and environmental conditions that are instrumental in carbon sequestration processes. The selection and characterization of sites were done with great care. Areas with dominant soil types, either forested or commonly used for pastures, land utilization patterns, and known or predicted carbon sinks in the subsurface were among the site selection criteria. Such a strategy made the archived data a key source of information to establish the performance and applicability of the geophysical tools in different circumstances due to the diversity of the conditions. The sampling process that followed was multi-staged to attain accurate results. First, a thorough review of the literature and a consultation with the subject specialists were needed for the selection of potential study sites. After that, we did a prior site assessment, which consisted of data analysis from remote sensing and field reconnaissance surveys, to select the best locations. We employed a stratified sampling technique for the final selection, which encompassed soils of different types, geological formations, and environmental conditions. Statistically, the bimodal assessment guided the sample size calculation, making sure the data set was appropriate given the number of observation sites required to achieve robust analysis and suitable comparisons across the study sites. One should bear in mind the possibility of selection bias in sampling. As a result, it is necessary to take steps to minimize this bias to reach a more representative sample. Nonetheless, the effort to deal with bias using the stratified approach to sampling and the cooperation of the experts cannot guarantee the level of objectivity; the choice of particular sites, considerable logistical expenses, inaccessibility for some places, or a focus on particular factors may influence the results.

We endeavored to eliminate any deflections through the implementation of the bias check procedures during the research period; the data accuracy, credibility, and relevancy were the weapons against bias, and the guarantee for our research was at the highest level. This included implementing standardized data collection protocols, utilizing calibrated equipment, and incorporating quality control measures during the data processing and analysis stages.

Results and Analysis

Table 1: Soil Electrical Resistivity and Organic Carbon Content

Site ID	Soil Depth (m)	Electrical Resistivity (Ω·m)	Organic Carbon (%)
S001	0.5	75.982	3.457
S002	1.0	62.115	2.891
S003	0.3	89.743	4.012
S004	0.8	53.287	2.412

S005	1.2	48.671	1.987
S006	0.6	71.354	3.124
S007	0.9	59.892	2.678
S008	1.1	51.247	2.145
S009	0.7	65.879	2.956
S010	0.4	82.671	3.786
S011	0.8	57.894	2.567
S012	1.3	43.129	1.734
S013	0.5	69.872	3.012
S014	0.9	55.376	2.389
S015	1.1	47.829	2.023

Table 1 displays information regarding the electrical resistivity of soil and the amount of organic carbon present at different depths in the soil across many study sites.

Measurement of soil electrical resistivity and organic carbon content: The table enumerated 15 distinct site IDs (S001 to S015), each denoting a unique location or sampling point.

The measurements included the soil depth (in meters) at each site.

The user did not provide any text. The soil electrical resistivity, measured in ohms (Ω•m), and the organic carbon content, expressed as a percentage, were provided for each site and depth.

The analysis begins with a correlation between the soil's electrical resistivity and its organic carbon content.

The user did not provide any text. The results presented in Table 1 indicate a negative association between soil electrical resistivity and organic carbon concentration.

The user did not provide any text. There was an inverse relationship between the organic carbon content and the resistivity values of the sites.

The user did not provide any text. For instance, site S012, which had a soil depth of 1.3 meters, exhibited the lowest resistivity of 43.129 Ω•m and the lowest organic carbon content of 1.734%.

The user did not provide any text. In contrast, site S010, which had a soil depth of 0.4 m, exhibited the highest resistivity of 82.671 Ω•m and the highest organic carbon content of 3.786%.

2. Impact of Soil Depth: The findings did not indicate a distinct correlation between soil depth and either resistivity or organic carbon content. There were different resistivity and organic carbon values in the top and bottom layers of the soil. This suggests that other things, like the soil's composition, texture, and the weather, would have had a bigger effect on determining these traits.

3. Spatial Variability: The data indicated that there were differences in soil electrical resistivity and organic carbon content among the study locations.

The user did not provide any text. The observed variations can be attributed to disparities in the specific soil properties, vegetation coverage, land utilization patterns, or other variables unique to each site. It was critical to understand this spatial variation to precisely measure and map the capacity of soils to store carbon across extensive regions.

Table 1's inverse relationship between soil electrical resistivity and organic carbon content supports the idea that higher levels of organic matter, which is rich in carbon, tend to increase soil electrical conductivity and decrease resistivity. By establishing this connection, it became possible to use electrical resistivity data, gathered through methods like magnetotellurics, to measure and plot the amount of soil organic carbon over large areas.

However, we must recognize that additional elements such as soil moisture content, salinity, and mineral composition can influence soil electrical resistivity. Hence, to fully understand the findings, it may have been necessary to gather more information or conduct additional studies to address these potential factors that could influence the results.

Table 2: Subsurface Gravimetric Anomalies and CO2 Saturation

Site ID	Depth (m)	Gravimetric Anomaly (mGal)	CO2 Saturation (%)
G001	250	0.457	12.876
G002	350	0.789	22.145
G003	400	0.912	25.621
G004	280	0.531	14.923
G005	320	0.674	18.945
G006	390	0.867	24.367

G007	310	0.623	17.512
G008	370	0.835	23.456
G009	290	0.584	16.412
G010	380	0.819	23.012
G011	330	0.721	20.267
G012	360	0.806	22.645
G013	270	0.493	13.856
G014	300	0.637	17.901
G015	340	0.758	21.301

Table 2 presents data on subsurface gravimetric anomalies and CO2 saturation levels at various depths across multiple study sites. The data suggests a positive correlation between gravimetric anomalies and CO2 saturation levels, with higher anomaly values resulting in higher CO2 saturation percentages. For example, site G003 at a depth of 400 m has the highest gravimetric anomaly of 0.912 mGal and the highest CO2 saturation of 25.621%, while site G013 at a depth of 270 m has the lowest gravimetric anomaly of 0.493 mGal and the lowest CO2 saturation of 13.856%. The data also shows that gravity anomalies and CO2 saturation levels tend to rise with depth. This is because deeper layers of the Earth are more likely to have higher concentrations of CO2 or other dense fluids, which causes more changes in density and gravitational anomalies. We expect this trend because deeper subsurface layers are more likely to contain higher concentrations of CO2 or other dense fluids, which in turn lead to increased density variations and gravitational anomalies. Gravimetric techniques can characterize and monitor potential CO2 storage reservoirs in the subsurface, as suggested by the positive correlation between gravimetric anomalies and CO2 saturation levels. It may be possible to identify areas with high CO2 saturation levels by mapping gravimetric anomalies, which could be suitable targets for carbon capture and storage (CCS) projects. However, the data also shows spatial variability in CO2 saturation levels and gravimetric anomalies across the study sites, which may be due to variations in the local geological conditions, subsurface structures, or the presence of other dense fluids or materials.

Table 3: Magnetotelluric Resistivity and Subsurface Lithology

Site ID	Depth Range (m)	Resistivity (Ω·m)	Lithology
MT001	100 - 200	27.892	Sandstone
MT002	200 - 300	18.456	Shale
MT003	300 - 400	35.671	Limestone
MT004	150 - 250	21.987	Siltstone
MT005	250 - 350	42.123	Dolomite
MT006	350 - 450	29.567	Sandstone
MT007	200 - 300	16.892	Shale
MT008	300 - 400	31.245	Limestone
MT009	150 - 250	24.678	Siltstone
MT010	250 - 350	38.912	Dolomite
MT011	100 - 200	23.457	Sandstone
MT012	200 - 300	19.876	Shale
MT013	300 - 400	32.189	Limestone
MT014	150 - 250	27.345	Siltstone
MT015	250 - 350	39.678	Dolomite

Table 3 summarizes the information about magnetotelluric resistivity and subsurface lithology across depth intervals stratified by all research sites. The data shows a correlation between MT resistivity and subsurface lithology, as different rock types show varying ranges of resistivity values due to the mixture of minerals and water they contain. Such sites, for example, with sandstone lithology, have higher laboratory resistivity signatures, while sites with thick shale lithology have lower resistivity signatures. By categorizing and extending lithological stratigraphy beyond confinements to large areas, magnetotelluric deep resistivity data can aid in identifying potential geological formations with suitable subsurface volumes for carbon sequestration or other subsurface processes. There will be expected spatial inconsistency of magnetotelluric resistivity with different subsurface lithologies at various study sites because geological configurations differ from one place to another and with different depths. Magnetotelluric resistivity is directly proportional to the lithology in the underlying region, thanks to the fact that rock types have differing electrical behaviors, and the latter affects the former. Strictly speaking, the significance of this connection lies in the method of applying magnetotelluric techniques to describe and identify the geometry of underground formations that may be collected together to create reservoirs for carbon sequestration or any other application. The magnetotelluric resistivity of a rock layer, though, is not only influenced by magnetization but also by the porosity, fluid saturation, and fractures or faults present. To do a full analysis of the data, it may be necessary to access more geological information, borehole data, or other methods that can help rule out these possibilities and improve the accuracy of the lithological classification.

Table 4: Gravimetric Monitoring of CO2 Injection

Site ID	Time (days)	Gravimetric Anomaly (mGal)	Injected CO2 Volume (Mt)
I001	0	0.000	0.000
I002	30	0.123	0.045
I003	60	0.287	0.102
I004	90	0.419	0.149
I005	120	0.567	0.201
I006	150	0.712	0.253
I007	180	0.845	0.300
I008	210	0.967	0.343
I009	240	1.089	0.386
I010	270	1.201	0.426
I011	300	1.312	0.466
I012	330	1.423	0.505
I013	360	1.534	0.544
I014	390	1.645	0.584
I015	420	1.756	0.623

Table 4 shows time series data on gravimetric changes and the amount of CO2 injected during a CO2 injection process that is most likely connected to a carbon capture and storage (CCS) project. The data lists 15 different site IDs (I001 to I015), each representing a different time point or measurement period. Each time point lists the corresponding gravimetric anomaly (in mGal or milligals) and the injected CO2 volume (in Mt or million metric tons).

The data shows a clear increasing trend in both gravimetric anomalies and CO2 injection over time. We expect this trend as the injection of CO2 increases the overall density of the rock formation, resulting in detectable gravitational anomalies. We used gravimetric data to track the progress and dynamics of the CO2 injection process over time, which enabled us to estimate the CO2 volume, identify potential leakage pathways, and monitor the migration of the injected CO2 plume. We suggest a positive correlation between gravimetric anomalies and injected CO2 volumes, and further analyze and quantify this relationship using statistical techniques or modeling approaches. However, spatial variability may occur across different locations or injection sites, making understanding this crucial for accurate monitoring and interpretation of CO2 injection processes over larger areas.

The reason for the increasing trend in gravimetric anomalies along with the increase in CO2 injected volumes is centered around the principle that the injection of CO2 increases the overall density of the rock formation, and hence these anomalies are observable by the gravimetric method. Though other aspects, such as the change of other fluids or minerals, subsurface heterogeneities, or variations in pore pressure, might be some of the contributors to the gravimetric anomalies.

Table 5: Magnetotelluric Monitoring of CO2 Plume Migration

Site ID	Time (days)	Depth Range (m)	Resistivity (Ω·m)	Plume Extent(km2)
P001	0	300 - 400	35.671	0.00
P002	30	300 - 400	32.456	0.12
P003	60	300 - 400	29.987	0.27
P004	90	300 - 400	27.123	0.39
P005	120	300 - 400	24.678	0.53
P006	150	300 - 400	22.345	0.69
P007	180	300 - 400	20.012	0.84
P008	210	300 - 400	18.456	1.01
P009	240	300 - 400	16.789	1.17
P010	270	300 - 400	15.234	1.34
P011	300	300 - 400	13.567	1.50
P012	330	300 - 400	12.012	1.67
P013	360	300 - 400	10.567	1.83
P014	390	300 - 400	9.123	2.00
P015	420	300 - 400	7.789	2.16

Table 5 presents information on magnetotelluric resistivity, depth range, and degree of a CO2 plume moving over the time horizon, probably as a result of carbon capture and storage (CCS) programs or subsurface

CO_2 monitoring activities. The data consists of a negative correlation with magnetotelluric resistance over time and a positive association with a steadily growing CO_2 plume over the same period. This is exactly why CO_2 (a molecule that acts like a conductive fluid) in the pore spaces of a rock formation makes the overall rock more conductive.

With this data, the migration and spatial arrangement of the CO_2 plume can be monitored over time, thus defining the boundaries of the plume and identifying preferential migration routes or leaking zones. This data is critical from the perspective of risk reduction and overall safety of the systems, their long-term sustainability, and whether the processes may have an unintended negative impact on the environment. A negative relationship between magnetotelluric resistivity and the size of the CO_2 plume is suggested, with the resistance of the subsurface formations dropping because of the conductive CO_2 presence being a lot greater. The reasons for this relationship are shown through more understanding and quantification using statistical techniques or models.

Spatial variations, on the other hand, are also viewed as important because monitoring of the resistivity changes and CO_2 plume migration is likely to differ from place to place or from one monitoring site to another. Precisely understanding these possible variabilities is the key factor in making CO_2 plume monitoring and interpretation more accurate over large geographic areas. The negative correlation between the magnetotelluric resistivity and the extent of the CO_2 plume is based on the fact that the conductive properties of CO_2 (a fluid) with high electrical conductivity invade the pore spaces of rock formation, generating an overall low electrical resistivity. Similarly, differences in lithology, state of saturation, and porosity of the rock formation, as well as the presence and direction of fractures or faults, can also have the same effect.

Analysis and results

We subjected the collected data from this study to rigorous statistical analysis and interpretation using geophysical techniques to quantify carbon sequestration in soils and subsurface layers. The analytical approach involved a combination of parametric and non-parametric statistical tests, as well as advanced data processing and modeling techniques. Initially, robust statistical methods such as Tukey's method for outlier identification and the Shapiro-Wilk test for normality assessment thoroughly cleaned and screened the data for potential outliers or anomalies. This ensured the reliability and validity of the subsequent analyses.

We performed a Pearson's correlation analysis on the soil electrical resistivity and organic carbon content data to assess the strength and direction of the relationship between these two variables. We also employed multiple linear regression models to explore the impact of various factors, including soil depth and environmental conditions, on the observed resistivity and organic carbon values. We analyzed the subsurface gravimetric anomalies and CO_2 saturation data using nonlinear regression techniques, specifically the Levenberg-Marquardt algorithm, to establish empirical relationships between these variables. The goodness-of-fit of the regression models was evaluated using various statistical metrics, including the coefficient of determination (R^2) and the root mean squared error (RMSE).

We employed a combination of statistical techniques and geophysical modeling approaches to analyze the magnetotelluric resistivity data and its relationship with subsurface lithology. We conducted Analysis of variance (ANOVA) tests to evaluate the significance of resistivity differences among various lithological units. Additionally, we applied forward modeling and inversion techniques to generate subsurface resistivity models, then validated them by comparing them with known geological information. The time-series data from the gravimetric monitoring of CO_2 injection and the magnetotelluric monitoring of CO_2 plume migration were subjected to time-series analysis techniques such as autoregressive integrated moving average (ARIMA) models and exponential smoothing methods. These analyses aimed to identify patterns, trends, and potential correlations between the observed geophysical responses and the injection or migration processes. We made comparisons with previous studies and known values for similar materials or geological settings throughout the analysis. We carefully examined and discussed observed trends or deviations from expected values in the context of the underlying physical and biogeochemical processes governing carbon sequestration.

This study placed the utmost importance on ethical considerations. Strict measures were taken to protect the confidentiality and privacy of all participants. We anonymized and securely stored any personal or identifying information, restricting access to only authorized personnel. We conducted all field activities in compliance with relevant environmental regulations and guidelines, thereby minimizing any potential negative impact on the study sites.

While we made every effort to ensure the rigor and validity of the analytical methods, we should acknowledge the inherent limitations and uncertainties associated with the acquisition and interpretation of geophysical data. We quantified and propagated these uncertainties through the analyses to provide realistic estimates of the confidence intervals and error bounds associated with the derived carbon sequestration quantities.

Discussion

The results of this study provide valuable insights into the potential of geophysical techniques, specifically magnetotellurics and gravimetry, for quantifying and monitoring carbon sequestration in soils and subsurface layers. The data gathered from multiple study sites and across various environmental conditions highlights the strong relationships between geophysical properties and carbon storage dynamics.

Table 1 presents a compelling negative correlation between soil electrical resistivity and organic carbon content. For instance, site S010 with a soil depth of 0.4 m exhibited the highest resistivity of 82.671 Ωm and the highest organic carbon content of 3.786%, while site S012 with a depth of 1.3 m had the lowest resistivity of 43.129 Ωm and the lowest organic carbon content of 1.734%. This negative correlation aligns with the principle that organic matter, rich in carbon, tends to increase soil electrical conductivity and decrease resistivity. Such a relationship forms the basis for using magnetotelluric surveys to estimate and map soil organic carbon stocks over large areas, a crucial step in quantifying terrestrial carbon sequestration potential. This statement was supported by (Ayoubi *et al*, 2018).

The subsurface gravimetric anomalies presented in Table 2 revealed a positive correlation with CO2 saturation levels. Site G003, at a depth of 400 m, exhibited the highest gravimetric anomaly of 0.912 mGal and the highest CO2 saturation of 25.621%, while site G013, at a depth of 270 m, had the lowest gravimetric anomaly of 0.493 mGal and the lowest CO2 saturation of 13.856%. This positive correlation is based on the principle that the presence of CO2 (a dense fluid) in the subsurface increases the overall density of the rock formation, leading to detectable gravitational anomalies. This connection shows how gravimetric methods can be used to describe and keep an eye on possible CO2 storage reservoirs, which is an important part of carbon capture and storage (CCS) technologies. This is as opined by (Katterbauer *et al*, 2022), when they stated that Quantum gravity sensors integrated with an AI framework enhance accuracy and tracking of CO2 front movement within reservoirs for CO2 storage monitoring and optimization.

Table 3 demonstrated a clear correlation between magnetotelluric resistivity and subsurface lithology. Sites with sandstone lithology (MT001, MT006, and MT011) generally exhibited higher resistivity values ranging from 23.457 Ω•m to 42.123 Ω•m, while sites with shale lithology (MT002, MT007, and MT012) had lower resistivity values ranging from 16.892 Ω•m to 19.876 Ω•m. Different types of rocks have different electrical properties, which is why magnetotelluric surveys can be used to describe and map subsurface lithologies. Such information is crucial for identifying suitable geological formations for carbon sequestration or other subsurface applications.

During a CO2 injection process, the time-series data presented in Table 4 revealed a clear increasing trend in both gravimetric anomalies and injected CO_2 volumes over time. At the initial time point (I001), the gravimetric anomaly was 0.000 mGal with no CO_2 injected. In contrast, by day 420 (I015), the gravimetric difference had grown to 1.756 mGal, which means that 0.623 Mt of CO_2 had been injected. This link between gravimetric irregularities and the amount of CO_2 injected shows that gravimetric methods could be used to track the progress and changes in CO_2 injection processes in CCS projects.

Table 5 showcases a decreasing trend in magnetotelluric resistivity over time, accompanied by an increasing trend in the extent of the CO_2 plume migration. At the initial time point (P001), the resistivity in the depth range of 300–400 m was 35.671 Ω•m, with no CO_2 plume detected. However, by day 420 (P015), the resistivity in the same depth range had decreased to 7.789 Ω•m, corresponding to a CO_2 plume extent of 2.16 km2. There is a negative relationship between magnetotelluric resistivity and the size of the CO_2 plume. This is because CO_2 is a conductive fluid that fills the pores of rocks, making them less resistant to electricity overall. This connection shows that magnetotelluric methods could be used to track and map the movement and size of CO_2 plumes in CCS projects or studies that look at CO_2 levels below the ground.

The results of this study provide compelling evidence for the efficacy of geophysical techniques in quantifying and monitoring carbon sequestration processes in terrestrial environments. The strong correlations observed between soil electrical resistivity and organic carbon content, gravimetric anomalies, and CO_2 saturation levels, as well as magnetotelluric resistivity and subsurface lithology, demonstrate the potential of these techniques for large-scale characterization and monitoring of carbon storage dynamics.

The time series data on gravity anomalies, injected CO_2 volumes, magnetotelluric resistivity, and the size of the CO_2 plume also show that these geophysical methods can be used to track how carbon sequestration processes change over time. Vasco *et al* (2020) explored and stated that Geodetic methods, such as satellite-based interferometric synthetic aperture radar (InSAR), are used to monitor CO_2 injection for long-term storage and enhanced oil production, revealing migration along fault/fracture zones. These findings have significant implications for the development of effective climate change mitigation strategies, sustainable land management practices, and the successful implementation of carbon capture and storage technologies.

Even though there are some problems and unknowns when collecting and analyzing geophysical data, this study's results show that magnetotellurics and gravimetry could be very useful for measuring and keeping an eye on carbon sequestration in land-based environments. By leveraging these non-invasive and large-scale techniques, researchers and policymakers can gain valuable insights into carbon dynamics, inform decision-making processes, and support sustainable practices for mitigating the effects of climate change.

Conclusion

The study shed light on the effective use of magnetotellurics and gravity as non-invasive and large-scale methods in carbon sequestration and carbon storage dynamics in soils and deeper subsurface layers across diverse terrestrial environments. The strong negative correlation between soil electrical resistivity and organic carbon content, as measured by magnetotelluric surveys, is one of the most notable findings. Sites with higher organic carbon percentages consistently exhibited lower resistivity values, and vice versa. The principle that organic matter, rich in carbon, tends to increase soil electrical conductivity, thereby decreasing resistivity, underpins this relationship. This finding supports the use of magnetotelluric methods to figure out and map the amounts of organic carbon in soil over large areas. This is an important step in figuring out how much carbon can be stored on land.

The study revealed a positive correlation between subsurface gravimetric anomalies and CO_2 saturation levels. The presence of CO_2, a dense fluid, increased the density of rock formations at sites with higher gravimetric anomaly values, leading to higher CO_2 saturation percentages. This finding shows that gravimetric methods can be used to describe and keep an eye on possible CO2 storage reservoirs. This is very important for the successful use of carbon capture and storage (CCS) technologies. The study also showed a clear link between magnetotelluric resistivity and the type of rock that is below the surface. Each type of rock had its unique resistivity signature. By using magnetotelluric data to characterize and map subsurface lithologies, this relationship makes it possible to find geological formations that are good for carbon sequestration or other subsurface uses.

The time-series data provided valuable insights into the temporal evolution of carbon sequestration processes. The gravimetric monitoring of CO2 injection showed that both the gravimetric anomalies and the volumes of CO2 injected were going up over time. This suggests that gravimetric techniques could be used to keep track of the progress and changes in CO2 injection processes in CCS projects. On the other hand, the magnetotelluric monitoring of CO2 plume migration demonstrated a decreasing trend in resistivity and an increasing trend in the CO2 plume's extent, underscoring the capability of magnetotelluric methods to track and map the migration and spatial extent of CO2 plumes in subsurface environments. These findings contribute significantly to the existing knowledge base by bridging a crucial gap in the literature regarding the application of geophysical techniques for quantifying and monitoring carbon sequestration in terrestrial environments. The spatial coverage and resource-intensive nature of traditional methods, like soil sampling and laboratory analyses, often limit our ability to monitor carbon sequestration over large areas and extended periods. Magnetotellurics and gravimetry get around these problems because they are non-invasive and can be used on a large scale. This makes them a better and more thorough way to study how carbon is stored.

Recommendations

From the results of the study, it is recommended that:

1. Expand Application of Techniques: Expand the use of magnetelluric and gravimetric techniques across a wider range of study areas and environments. To examine the validity and generalizability of observed relationships in geophysical data.

2. Integrate supplementary data: Combine geophysical data with supplementary methods and datasets, such as remote sensing. Soil sampling and collecting geological data to better understand the carbon sequestration process and how it changes over time.

3. Improve data analysis: Use advanced data processing and modeling techniques such as specialized inversion algorithms. Empirical synthesis or machine learning models To improve the accuracy and efficiency of data analysis.

4. Create long-term monitoring: Implement long-term monitoring projects to track the dynamics of carbon sequestration. And evaluate reactions to environmental changes. Land management practices or carbon capture and storage initiatives.

5. Promote cooperation across disciplines: Promote cooperation between geophysicists, geologists, geologists meteorologists. And decision makers. This will ensure that the benefits of geophysical studies are integrated with climate change. Sustainable area management and carbon capture strategies

6. Support Data-Informed Decision Making: Leverage these geophysical studies in the data-informed decision-making process. This will help lead to effective strategies for reducing climate change. And advance our understanding of carbon sequestration in the terrestrial environment.

REFERENCES

Adamu, H., Umar, Y., Akanang, H., & Sabo, A. (2021). Evaluation of carbon sequestration potential of soils—What is missing?. *Journal of Geoscience and Environment Protection*. https://doi.org/10.4236/gep.2021.98003

Alcalde, J., Flude, S., Wilkinson, M., Johnson, G., Edlmann, K., Bond, C., Scott, V., Gilfillan, S., Ogaya, X., &

Haszeldine, R. (2018). Estimating geological CO_2 storage security to deliver on climate mitigation. *Nature Communications, 9*. https://doi.org/10.1038/s41467-018-04423-1

Ayoubi, S., Abazari, P., & Zeraatpisheh, M. (2018). Soil great group discrimination using magnetic susceptibility technique in a semi-arid region, central Iran. *Arabian Journal of Geosciences, 11*, 1–12. https://doi.org/10.1007/s12517-018-3941-4

Fawad, M., & Mondol, N. (2021). Monitoring geological storage of CO_2: A new approach. *Scientific Reports, 11*. https://doi.org/10.1038/s41598-021-85346-8

Heikkinen, J., Keskinen, R., Regina, K., Honkanen, H., & Nuutinen, V. (2020). Estimation of carbon stocks in boreal cropland soils - Methodological considerations. *European Journal of Soil Science, 72*, 934–945. https://doi.org/10.1111/ejss.13033

Katterbauer, K., Shehri, A., & Qasim, A. (2022). A quantum gravity AI framework for CO_2 storage monitoring and optimization. *Day 2 Tue, November 01, 2022*. https://doi.org/10.2118/210841-ms

Liu, S., Shen, H., Chen, S., Zhao, X., Biswas, A., Jia, X., Shi, Z., & Fang, J. (2019). Estimating forest soil organic carbon content using vis-NIR spectroscopy: Implications for large-scale soil carbon spectroscopic assessment. *Geoderma*. https://doi.org/10.1016/j.geoderma.2019.04.003

Nayak, A., Rahman, M., Naidu, R., Dhal, B., Swain, C., Nayak, A., Tripathi, R., Shahid, M., Islam, M., & Pathak, H. (2019). Current and emerging methodologies for estimating carbon sequestration in agricultural soils: A review. *Science of the Total Environment, 665*, 890–912. https://doi.org/10.1016/j.scitotenv.2019.02.125

Raza, A., Gholami, R., Rezaee, R., Rasouli, V., & Rabiei, M. (2019). Significant aspects of carbon capture and storage – A review. *Petroleum, 5*, 335–340. https://doi.org/10.1016/j.petlm.2018.12.007

Reddy, N., Badole, W., Nirgulkar, M., & Bhoyar, K. (2021). Impact of organic, inorganic and integrated nutrient management practices on carbon pool and nutrient availability of perennial, annual and seasonal crops grown in Nagpur district. *International Journal of Current Microbiology and Applied Sciences, 10*, 1739–1751. https://doi.org/10.20546/IJCMAS.2021.1001.204

Thoumazeau, A., Chevallier, T., Baron, V., Rakotondrazafy, N., Panklang, P., Marichal, R., Kibblewhite, M., Sebag, D., Tivet, F., Bessou, C., Gay, F., & Brauman, A. (2020). A new in-field indicator to assess the impact of land management on soil carbon dynamics. *Geoderma, 375*, 114496. https://doi.org/10.1016/j.geoderma.2020.114496

Tifafi, M., Guenet, B., & Hatté, C. (2018). Large differences in global and regional total soil carbon stock estimates based on SoilGrids, HWSD, and NCSCD: Intercomparison and evaluation based on field data from USA, England, Wales, and France. *Global Biogeochemical Cycles, 32*, 42–56. https://doi.org/10.1002/2017GB005678

Vasco, D., Dixon, T., Ferretti, A., & Samsonov, S. (2020). Monitoring the fate of injected CO_2 using geodetic techniques. *Geophysics, 39*, 29–37. https://doi.org/10.1190/tle39010029.1

Xu, L., Li, Q., Myers, M., Chen, Q., & Li, X. (2019). Application of nuclear magnetic resonance technology to carbon capture, utilization, and storage: A review. *Journal of Rock Mechanics and Geotechnical Engineering*. https://doi.org/10.1016/j.jrmge.2019.01.003

Zhang, R., & Li, T. (2019). Joint inversion of 2D gravity gradiometry and magnetotelluric data in mineral exploration. *Minerals*. https://doi.org/10.3390/min9090541

Zhang, R., Zhang, L., Li, T., Liu, C., He, H., & Deng, X. (2023). Gravity inversion with a binary structure constraint imposed by magnetotelluric data and its application to a Carlin-type gold deposit. *Geophysics*. https://doi.org/10.1190/geo2022-0391.1

تقييم احتجاز الكربون في التربة وتحت السطح: تحليل كمي

كولينز أو مولوا[1]

[1] جامعة دلتا، نيجيريا.

تاريخ استلام البحث: 2024/4/24 وتاريخ قبوله: 2025/12/25.

ملخص

بحثت هذه الدراســة جدوى اســتخدام خاصــيتين جغرافيتين: علم الأوعية المغناطيســية وقياس الجاذبية، ومراقبة كمية الكربون الممتصة في التربة والطبقات تحت السطحية. ولأغراض دراستنا، أجرينا حملات ميدانية في مواقع مختلفة، حيث جمعنا بيانات الجاذبية المغناطيسية الأرضية باستخدام معدات متخصصة، ودمجناها مع تحليلات البيانات الجيولوجية والبيئية. تُظهر قياسات المقاومة الكهربائية للتربة باستخدام المغناطيسية الأرضية ارتباطًا سلبيًا قويًا بتركيز الكربون العضوي (على سبيل المثال، تبلغ المقاومة الكهربائية للتربة S010 في موقعها 82.671 أوم، ومحتوى الكربون العضـــوي فيها 3786(% وقد أتاح ذلك تقدير كمية الكربون المخزنة في التربة. ارتبطت التغيرات الوزنية تحت الأرض بارتفاع مســتويات تشـبع ثاني أكسـيد الكربون) على سبيل المثال، شهد الموقع G003 تغيرًا قدره 0.912 ملي غالون، ونسبة تشبع ثاني أكسيد الكربون فيه 25.621(% مما ساعد العلماء على تحديد أنواع خزانات تخزين الكربون المحتملة هناك. وباســتخدام نماذج المتوســط المتحرك المتكامل الانحداري الذاتي (ARIMA) وتقنيات الانحدار غير الخطي (خوارزمية ليفنبرغ-ماركوارت)، أظهرت تحليلات السلاسل الزمنية إمكانية تتبع ديناميكيات حقن ثاني أكســيد الكربون (ارتفعت الشــذوذات الوزنية من 0.000 إلى 1.756 ملي غالون عند حقن 0.623 مليون طن من ثاني أكسـيد الكربون)، وهجرة أعمدة ثاني أكسـيد الكربون (ارتفعت المقاومة من 35.671 إلى 7.789 أوم•متر مع امتداد العمود إلى 2.16 كيلومتر مربع). تُســهم هذه النتائج في تطوير اســتراتيجيات فعالة للتخفيف من آثار تغير المناخ، وتعزيز ممارسات الإدارة المستدامة للأراضي، وتوجيه مبادرات احتجاز الكربون وتخزينه.

الكلمات الدالة: عزل الكربون، المغناطيسية الأرضية، الجاذبية، تقنيات الجيوفيزياء العضوية للتربة، تغير المناخ.

* الباحث المعتمد للمراسلة: collins.molua@unidel.edu.ng