Modeling of carbon sequestration with land use and land cover in the northeastern part of the Nile Delta, Egypt

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Abstract
The world is currently concerned about the phenomenon of climate change and global warming because of the natural disasters that threaten the lives of living organisms on the surface of the earth. Despite this, there is a dearth of studies dealing with reducing carbon emissions in Egypt. We needed to cover this defect in an important area of Egypt, which is the eastern delta region including Manzala Lake. Land use and land cover (LU/LC) represents a vital role in carbon regulation in coastal areas. Our study uses three Landsat images in 2001, 2013, and 2021 to estimate the amount of carbon storage and sequestration and used Land Change Modeler (LCM) with Cellular Automata Markov Chain (CA-MC) model to predict land cover changes in 2031. Results show that in the period between 2013 and 2021, about half of the floating plants have been destroyed and removed. Our results demonstrate that the increased area for agricultural lands from 2013 to 2021 (2306 Mg C/km²) leads to an increased amount of carbon storage but the decreased area for floating plants (-4508 Mg C/km²) leads to a decrease in carbon storage. Results showed that a remarkable decrease in carbon storage in the future was attributed to anthropogenic activities in the study area and also as a result of the unexploiting of environmental resources. Finally, the total cost of carbon was 1323.4, 1437.9, 1184.8, and 1296.5 $US/ha for 2001, 2013, 2021, and 2032, respectively. Results showed that the minimum cost for 2021 that a noticeable shortage due to the removal of vegetation and an increase in the area of lake water. These conversions have to some extent affected the capacity of coastal habitats to sequester and store CO₂. For carbon storage, we recommend afforestation of desert areas. The current design for carbon storage and sequestration is a good guide for government and decision makers for sustainable development, climatic regulation, and carbon budget.

Keywords Manzala Lake · Remote sensing · GIS · Markov chain · Carbon sequestration · Ecosystem services · InVEST model

Introduction
Ecosystem services (ESs) refer to ecological processes’ benefits and their effectiveness for human well-being (Yua et al. 2019). These ecosystems provide many benefits and services that contribute to regulatory functions such as erosion protection, hydrological regimes, flood risk reduction, and water purification (Mouttaki et al. 2021). In addition to these services, coastal wetlands also contribute to climate regulation by sequestering and storing carbon captured from the atmosphere and ocean (Herr et al. 2017). Land use/cover change (LUCC) has an important effect on the supply and value of several ESs, mainly climate regulating services, due to fundamental changes that occur in the structure and function of forests, agriculture, and other ecosystems over time (Fu et al. 2017). Such Ecosystem functions affect carbon sequestration. Changes in land use including forest clearance for agriculture, settlement, and industrial expansion have contributed about 136 (± 55) Gt carbon or one-third of total anthropogenic emissions of carbon dioxide (CO₂) to the atmosphere over the past 150 years (Watson et al. 2000). Lal (2004) stated that carbon storage of forests, rangelands, and other land ecosystems is four times more than the atmosphere (3060 Gt vs. 760 Gt). Furthermore, concentration of carbon in plants and soil over time will lead to excess...
carbon sequestration every year. The basic resources for both humans and nature are threatened by both global and regional pressures (IPBES 2019). Therefore, principles for measuring and valuation of ecosystem services are attracting attention for their possible to support the resolution of environmental problems (Nerlich et al. 2013). Carbon sequestration describes the long-term carbon storage in soil, plant, and other forms to either mitigate or slow down climatic change (Canadell and Raupach 2008; Eggleston et al. 2006; Gallant et al. 2020). In this context, terrestrial ecosystems, including forest, orchard, and agricultural ecosystems, play a vital part in carbon cycling and storage (Sil et al. 2017). Among terrestrial ecosystems, agriculture often acts as a source of greenhouse gases (Kanime et al. 2013). Population growth, industrialization, urbanization, deforestation, and conversion of natural vegetation into cultivable land to meet the ever-growing demand for food crops are consider a major source of CO₂ emission (Molotoks et al. 2018). The soil which in turn increases the atmospheric carbon and causes reduction of the terrestrial carbon pool (Lal 2019). Japelaghi et al. (2022) mentioned that the concept of ecosystem services in land cover management issues, selecting areas for protection, and ecosystem services compensation requires information about the spatial distribution of services. Due to the importance of ecosystem services, there is a need for suitable software and accurate prediction models that can provide data for ecosystem services to decision makers, and examine the results of land cover management on services. One of the ecosystem services mapping software, the integrated software ecosystem services pricing and the interaction between them, is the Ecosystem Services Modeler, which is a vertical application within the TerrSet System. It is a spatially powerful decision support system to evaluate ecosystem services, which is based entirely on InVEST toolset developed by the Natural Capital Project. The main aim of the present study is to study the stored or lost carbon over the study period to solve an environmental problem that costs the state huge sums to eliminate and reduce.

Lake Manzala was selected as a case study for carbon stock due to the recent work for purifying and developing the lake. Lake Manzala has made great strides towards the lake’srestoring of its luster and nature for being one of the largest lakes in Northern Egypt due to ending violations to the laws regulating fishing in it. Lake Manzala remains the largest of the Nile Delta lakes and has undergone substantial recent changes particularly over the last 30 years. To achieve the main aim of the study, land change modler and Cellular Automata Markov Chain (CA-MC) were applied for studying the LU/LC change on carbon storage and sequestration. The aims of this paper are (1) to examine the LU/LC process in the study area during 2001, 2013, 2021, and 2031; (2) to monitor modeling of carbon storage and sequestration and explore the mechanisms and cost using TerrSet; (3) to enumerate value in carbon storage and sequestration associated with LU/LC; (4) to understand the spatial distribution and characteristics of carbon storage and sequestration over time based on the landscape scale to achieve comprehensive information for decision-making processes of ecosystem management.

Materials and methods

Study area

The Nile Delta is one of the world’s largest river deltas from Alexandria in the west to Port Said in the east; it covers 240 km (150 mi) of the Mediterranean coastline and is a rich agricultural region. From north to south, the delta is approximately 160 km (99 mi) in length. The Delta begins slightly downriver from Cairo. The study area includes the northeastern part of the Nile Delta, Egypt, as shown in Fig. 1. The study area includes one of the Northern delta lakes; Manzala Lake. Manzala Lake is the largest coastal lake in Egypt with an area of about 404.69 square kilometers and its depth is 1.15 m. Manzala Lake is located in the northeastern part of the Nile Delta, a vulnerable sandy beach ridge separating the lake from the sea, while it connected to the Mediterranean Sea through Boughaz El-Gamil inlets. It is typically located between longitudes 31° 45′ and 32° 22′ E and latitudes 31° 00′ and 31° 35′ N. km². The lake is shallow, typically ranging from 0.7 to 1.5 m in considerable depth. It is connected to the North by the Mediterranean Sea, East by Suez Canal, South by El-Salam Canal, and West by Damietta Branch of River Nile.

Data acquisition and preparation

Landsat images were acquired from: http://glovis.usgs.gov. The study area was located in one scene: path 138, raw 76. Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM) and Operational Land Imager (OLI) images were acquired in 2001, 2013, and 2021, respectively. The atmospheric correction method is used to correct primarily the wavelengths of visible near-infrared and shortwave-infrared information (Abd El-Hamid et al. 2019). Images were registered in Universal Transverse Mercator Projection (UTM-WGS 84 and zone 36 N). A flowchart was presented showing the details of methodology as shown in Fig. 2.

Land cover classification for land cover change detection

The calibrated Landsat image was processed to map water, urban and agricultural lands though applying the unsupervised classification (i.e., ISODATA) using ENVI 5.3
Landsat images were classified using maximum likelihood and object-oriented methods into six classes: open water, mixed water, agricultural area, bare lands, floating plants, and built-up area using ENVI 5.3 software. Maximum likelihood classification (MLC) is a popular method for determining a known class of distributions as the maximum for a given statistic. The root of maximum likelihood classification can be traced back (Sun et al. 2013). Training areas were established by selecting one or more polygons for each class. Pixels that fall within the training area were taken as the training pixels for a particular class. Land cover change detection and transition modeling were carried out using Land Change Modeler (LCM) in TerrSet Software.

Markov and CA-Markov chain model

A Markov chain is a random process of a limited condition in a system with transition probabilities. Markov and Cellular automata (CA) were applied in the present study for simulation and prediction of LU/LC with probability using Idrisi Selva 17.0. Using transition potential models as a foundation, LCM uses Markov Chain analysis to project the expected quantity of change and a competitive land allocation model to determine scenarios for a specified future date. Options exist to incorporate planning interventions such as incentives and constraints, proposed reserve areas, and infrastructural changes (Behbahani and Heidari-zadi 2019). It is important to note that CA–Markov model has been used recently in dynamic spatial phenomenon’s simulation and future land use change prediction.

\[ S(t+1) = (p_{ij} + S(t)) \]
\[ P_{ij} = \begin{pmatrix}
  p_{11} & p_{12} & \cdots & p_{1n} \\
  p_{21} & p_{22} & \cdots & p_{2n} \\
  \vdots & \vdots & \ddots & \vdots \\
  p_{n1} & p_{n2} & \cdots & p_{nn}
\end{pmatrix} \]

where \( S(t) \) is the state of the system at time \( t \), \( S(t+1) \) is the value and state of the system at a time \( (t+1) \); \( P_{ij} \) is the transition probability matrix. Based on the results of model validation, if model accuracy is more than 85%, there is a good situation and if it is less, the model should be repeated (Japelaghi et al. 2019). At last, when model validation gave suitable results, land cover maps of 2013 and 2021 (as T2 and T3) were defined as input maps and land cover change prediction will occur in the future in 2031.

Model validation

Considering the importance of model validation, a Kappa coefficient was carried out using LCM in TerrSet software to determine model accuracy and persistence based on a comparison of derived land cover maps using Landsat image classification and change simulation in 2021.

Modeling of carbon storage and sequestration through TerrSet

The carbon module uses a simplified carbon cycle to estimate the amount of static carbon storage and dynamic sequestration for each cell in a specific region (He et al. 2016; Tallis et al. 2013). This module considers four carbon
pools, including above-ground carbon density, belowground carbon density, soil organic carbon, and dead organic matter (Tallis et al. 2013). The calculation of the carbon storage \( C_{m,i,j} \) in a given grid cell \((i, j)\) with land use type “m” can be achieved by Eq. 1:

\[
C_{m,i,j} = A \times (C_{am,i,j} + C_{bm,i,j} + C_{sm,i,j} + C_{dm,i,j})
\] (1)

In this formula, \( A \) is the real area of each grid cell (ha). Also, \( C_{am,i,j} \), \( C_{bm,i,j} \), \( C_{sm,i,j} \), and \( C_{dm,i,j} \) are the above-ground carbon density, belowground carbon density, soil organic carbon density, and dead organic matter carbon density \((i, j)\), respectively. Finally, carbon storage “\( C \)” and carbon sequestration “\( S \)” can be calculated by Eqs. 2 and 3 for the whole case study region (Aalde et al. 2006):

\[
C = \sum_{m=1}^{n} C_{m,i,j}
\] (2)

\[
S = C^{T2} - C^{T1}
\] (3)

In Eq. 3, \( C^{T2} \) and \( C^{T1} \) demonstrate static carbon storage in years \( T2 \) and \( T1 \) \((T2 > T1)\). The needed data for running the carbon storage model were the LULC map and the biophysical table containing columns of LULC, “\( C_{above} \),” “\( C_{below} \),” “\( C_{soil} \),” and “\( C_{dead} \).” The required biophysical data are obtained from sampling and field experiments by Liang et al. (2017) and the InVEST user’s guide (Sharp et al. 2020). The data regarding the carbon sequestration model were a current and future LULC scenarios map for calculating the net change of carbon storage pixel by pixel over time. The last part of carbon modeling is estimating the economic value distribution of carbon sequestration/loss (not storage) under each scenario over time. This function, Eq. 4, requires three inputs, including I) “\( V \),” the monetary value of each unit of carbon, II) “\( r \),” a monetary discount rate, and III) “\( c \),” the change in the value of carbon sequestration over time (Tallis et al. 2013):
Fig. 3  LU/LC and percentage (%) in 2001, 2013, 2021 and 2031, respectively
The first input “V” is estimated based on the social cost of carbon (SCC) that is released Mg of carbon in the atmosphere in case of excess of the threshold. Some studies (Haigh et al. 2020) estimated the total values of carbon sequestration as SCC based on the damages caused by releasing an additional ton of carbon into the atmosphere. There are some sufficient criteria to determine this value, including differences in landscape, applied discount rate, and carbon cost and benefit of carbon sequestration. Estimated values for each ton of carbon range widely from $32 US dollars (Nordhaus 2007) to $326 US dollars (Stern 2007). To estimate the cost of loss per ton of carbon or the benefit from storing per ton of carbon, an alternative method is to regard the equivalent cost of carbon sequestration per ton. This method considers the cost of storing carbon in public facilities such as power plants. The mentioned studies estimated this price equal to be approximately $110 US dollars. In our study, the same cost per ton of carbon was considered. The second input, “r,” is the discount rate that expresses the preference of the community over immediate benefits and future benefits. Based on the cost–benefit evaluation of an environmental assessment by the US government, this input is set to 7% in the carbon module. This rate varies for different landscape conditions and local requirements. The third data, “c,” reports the change of carbon price in the form of the annual rate. These data demonstrate the sequestered carbon value resulting from emissions impact on damages associated with expected climate change. The default value is set to zero. A number was greater than zero means that the social value of carbon sequestration in the future is less than its value of the present time. In our study, due to attend the high probability of exacerbation of the impacts induced by climate change, the default value of zero was considered.

### Results

#### Land cover change and predicting using Markov chain

In the present study, six classes were acquired using supervised classification; open water, agricultural lands, floating plants, mixed water, bare lands, and built-up as shown in Fig. 3. From the present study, in 2001, 44.7% was covered by open water, followed by agricultural lands 23.4%, floating plants 13.1%, mixed water 9%, built-up 6.64%, and bare lands 3.01%. In 2013, 43.25% was covered by open water, followed by agricultural lands 15.75%, mixed water 14.34%, floating plants 13%, built-up 12.27%, and bare lands 1.39%. In 2021, 49.35% was covered by open water; followed by agriculture lands 22.04%, mixed water 18.78%, built-up 8.19%, bare lands 0.92%, and floating plants 0.70%. The produced land cover maps using Land Change Modeler (LCM) predicts land cover maps for 2031 and visualizes the distribution of land cover changes in the study area in the future. Based on a historical scenario in 2031, 48.06% was covered by open water, followed by agricultural lands 21.68%, floating plants 13.05%, mixed water 9.77%, built-up 4.67%, and bare lands 2.77% as shown in Table 1. The highest area (km²) was calculated as the following sequence as shown in Fig. 4; for open water: 2021 > 2031 > 2001 > 2013, for agricultural lands: 2001 > 2031 > 2021 > 2013, for floating plants: 2001 > 2013 > 2021, for mixed water: 2021 > 2013 > 2031 > 2001, for bare lands: 2001 > 2031 > 2013 > 2021, and for built-up: 2013 > 2021 > 2001 > 2031.

#### Transition probability of LU/LC

A transition probability matrix for different LU/LC classes from the year 2013 to 2021 has been generated using the Markov chain analysis which is a stochastic approach that expresses the likelihood of the fact that a pixel of a given class will change to any other class for the given period. The periods from 2013 to 2021 recorded a remarkable gain in open water that reflects the drilling processes inside Manzala Lake. In the present study, there is a high value at 0.905 probabilities that reflects the drilling processes inside Manzala Lake. In the present study, in 2001, 44.7% was covered by open water, followed by agricultural lands 23.4%, floating plants 13.1%, mixed water 9%, built-up 6.64%, and bare lands 3.01%.

### Table 1 Area (km²) and percentage (%) of LU/LC along the study area

| LU/LC          | Area (km² & percent) | 2001–2013 | 2013–2021 | 2021–2031 | 2001–2031 |
|----------------|----------------------|-----------|-----------|-----------|-----------|
|                |                      | km²       |           |           |           |
| Open water     | 1311 (44.70%)        | 1268 (43.25%) | 1447 (49.35%) | 1409 (48.06%) | – 43 | 179 | – 38 | 98 |
| Agriculture lands | 686 (23.43%) | 462 (15.75%) | 646 (22.04%) | 636 (21.68%) | – 225 | 184 | – 11 | – 51 |
| Floating plants | 386 (13.17%) | 381 (13%) | 21 (0.70%) | 383 (13.05%) | – 5 | – 361 | 362 | – 4 |
| Mixed water    | 265 (9.05%) | 420 (14.34%) | 550 (18.78%) | 287 (9.77%) | 155 | 130 | – 264 | 21 |
| Bare lands     | 88 (3.01%) | 41 (1.39%) | 27 (0.92%) | 81 (2.77%) | – 47 | – 14 | 54 | – 7 |
| Built-up       | 195 (6.64%) | 360 (12.27%) | 241 (8.21%) | 137 (4.67%) | 165 | – 119 | – 104 | – 58 |

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the open water will remain in the same class and a low probability of conversion of open water into other classes where about 0.01 of floating plants remain in the same class. All conversion confirms the governmental processes in the study area. Results showed that the highest gain was observed in mixed water and the highest loss occurred in floating plants as shown in Fig. 5. Finally, about 95%, 67%, 1%, 45%, 37%, and 45% of open water, agricultural lands, floating plants, mixed water, bare lands and built-up area are remain constant and not change from 2013 to 2021, respectively, as shown in Table 2.

Model validation

Model validation was carried out using a validation module in LCM in TerrSet software. In this section, the validated model was calibrated by comparing the simulated and actual LU/LC map for 2021. Two validation models were applied for 2001 to 2013 and 2013 to 2021; with the kappa statistics such as Kstandard (0.47), Kno (0.55), Klocation (0.62), and Klocation Strata (0.62), for the period from 2013–2021, the overall agreement of 0.82 indicates the reasonable performance (78%) of the model. In addition, the kappa statistics are Kstandard (0.42), Kno (0.55), Klocation (0.62), and Klocation Strata (0.62).

Carbon storage and sequestration

The carbon model’s final output was the economic value distribution of carbon sequestration under the suggested predictive scenario, as shown in Fig. 6. In the present study, open water has no carbon stock in all periods of the study where floating plants represent the high amount of carbon stock. In 2001 and 2013, floating plants representing 4.6 Mg C/km² had the highest mean carbon storage whereas bare lands (0.4 and 0.2 Mg C/km²) 2001 and 2013, respectively, which had the lowest mean carbon storage. In 2021, built-up representing 6.6 Mg C/km² was the land use type which had the highest mean carbon storage where bare lands at 0.1 Mg C/km² were the land use type which had the lowest mean carbon storage. In 2031, floating plants at 4.6 Mg C/km² were the land use type that had the highest mean carbon storage whereas bare lands at 0.3 Mg C/km² were the land use type that had the lowest mean carbon storage as shown in Fig. 7. The total amount of carbon stock increased from 2001 to 2013 and decreased from 2013 to 2021 and for validation, a statistical model was performed with $R^2$ equal to 1 as shown in Fig. 8. Finally, the conversion of floating plants and agricultural areas to other classes leads to low carbon stock, so that floating plants have occupied the most values of carbon sequestration.

Economic valuation of carbon

Our economic valuation of carbon sequestration was 30.19, –66.78, and 29.48 million $US for 2001–2013, 2013–2021 and 2021–2031, respectively. The maximum annual rate was 23.48 million $US in the period 2001–2013, whereas the minimum annual rate was –51.94 million $US in the period 2013–2021. For hectares, the annual rate was 8.87, –19.62, and 8.66 ha⁻¹ year⁻¹ for 2001–2013, 2013–2021, and 2021–2031, respectively, as shown in Table 3.

Discussion

Manzala Lake is a strategic environmental Lake of Egypt during last decade that was characterized by the extensive land cover change that affects negatively on the ecosystem services value. For Manzala lake, 12 million EGP was approved for developing the lake due to different problems (Egy-map 2020; Fahmy 2021), including the
shrinking of the area due to erosion and drying of the soil and the growth of aquatic plants, such as Nile roses and reeds, which led to impeding the movement of water, and impact the fish wealth as well. According to the results of the present study, the little decrease in Built-up areas may be attributed to some new projects that lead to an
increase in the income of the country. The present study confirms the drilling process during the periods from 2013 to 2021 and the prediction image in 2031 confirms continuity of drilling. Urbanization may impact negatively vegetation. Urbanization exerts intensive anthropogenic pressure on the study area. These places are highly modified and impacted by a large number of human activities. It was shown that open and mixed water was the highest class in 2021 than other periods where the area of floating plants was decreased due to some governmental processes inside Manzala Lake. These reductions in carbon storage will have resulted in a corresponding degree of increased carbon emissions. The expansion of cultivated land and urban areas had a slight influence on carbon storage, as this change in LULC has mainly affected wet lawns and the edges of unused land (Kacem et al. 2022). Finally, the model that gives the relationship among a year of study and amount of carbon by hectare was calculated with high $R^2$. Dense forests had higher biomass carbon stock compared to open forests and that grassland. The present study, total sequestered carbon is continually decreasing because of human disturbances which will cause ecosystem services damage and at last human health will be affected. Also, the impact on the net ecosystem service values caused by the large change in total value of sequestered carbon shows that human activities in study area impose
a high economic damage (Akber et al. 2018). Rajput et al. (2017) and Solomon et al. (2017) found higher biomass carbon in forest ecosystems than other ecosystems. Mekuria (2013) said that dense forest had higher total carbon stock followed by open forest, grassland, cultivated land, and bare land in this study. Our results showed that agricultural lands and floating plants have large contribution on total value of ES as provides higher amount of carbon storage and sequestration. The average total carbon stock of the dense forest was 181.8 Mg ha$^{-1}$. Our results of the present study will be helpful for understanding the pattern of C storage and C sequestration potential in various land uses having similarity in locality factors. Abou Samra (2021) recommends expanding the vegetation cover to reduce further increases in LST and control ecological damage which agrees with our results for increasing the carbon stock. Finally, we deduced a mathematical model that describes this change and is easy to use to predict what will happen in the coming years. And we deduced the expected shape of the region 10 years from now (2031) as shown in Fig. 9. Our results are in line with Sil et al. 2017, who found that the value of carbon sequestration with a different carbon prices ranged from a minimum of US$ 13.5 ha$^{-1}$ year$^{-1}$ when converting forest to grassland. Padilla et al. (2010) showed that in the case of intense human activities (conversion of forest to human settlement and farmland), the spatial distribution of carbon sequestration value varied from a minimum of US$ –1361.23 ha$^{-1}$ year$^{-1}$ to a maximum of US$ 230.43 ha$^{-1}$ year$^{-1}$. The differences between our results reflect the uncertainty of the economic valuation of carbon storage (Sil et al. 2017) and the preferences of future societies on climate mitigation (Fleurbaey et al. 2019), which are mainly derived from different prices of carbon and emission trajectories. Our study determines that even with the limited data available for simulated and current carbon storage could be an acceptable demonstration of real carbon storage in the study area. In this sense, there is a need to strengthen research in this field with further studies.

### Conclusion

This paper investigates the value of carbon on the northeastern part of the Nile Delta of Egypt, based on LULC analysis. In the present paper, using Landsat satellite images, land cover maps were produced and used as the inputs of LCM. Land cover change prediction was carried out using Markov Chain. Our main object was to consider the spatiotemporal impacts of land use/cover change forces on carbon storage and sequestration, as well as the associated cost of those Changes. Such estimates in developing countries, such as Egypt, have typically been associated with poor quality data concerns, weak technical knowledge to implement appropriate assessment methods, and centralization on a single time point. The current study examines the impact of governmental works on carbon storage in the Manzala Lake area and estimates the annual storage rate and the average cost in dollars. And we deduced a mathematical model that describes that change and is easy to use to predict what will happen in the coming years. And we deduced the expected shape of the region ten years from now (in 2031). The research also presented a study of the impact of that great change on the change in vegetation cover and human activity in the region. The study presented some important recommendations to remedy some defects, improve the environmental situation of the region, and increase its effectiveness in carbon absorption and storage. The present study showed that land use/cover change can strongly influence the spatial pattern of carbon storage and sequestration in the northeastern part of the Nile delta (Manzala Lake) over time. The future

| Table 3 | Total economic costs (million $US) and rate ($US ha$^{-1}$) due to carbon sequestration |
|---------|--------------------------------------------------------------------------------------------|
| **Discounts rate** | | |
| **LU/LC translations** | **Value (million $US)** | **Rate ($US/ha)** | **Value (million $US)** | **Rate ($US/ha)** | **Value (million $US)** | **Rate ($US/ha)** |
| | | | | | | | |
| 2001–2013 | 30.19 | 9.44 | 23.48 | 9.25 | | |
| 2013–2021 | –66.78 | –20.88 | –51.94 | –20.46 | | |
| 2021–2031 | 29.48 | 9.22 | 22.93 | 9.03 | | |
| **Total cost** | | | | | | | |
| **2001** | **2013** | **2021** | **2031** | | | |
| **Total cost $US/ha** | 1323.4 | 1437.9 | 1184.8 | 1296.5 | | |
| **Total cost for year $US** | 387,991,141 | 42,1540,516 | 347,338,532 | 380,089,742 | | |
| **Total cost for all years $US** | 1,536,959,930 | | | | | |

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landscape under different scenarios is likely to affect this value. Under the environmentally sound planning scenario, the potential of the plain for regulating ecosystem services such as carbon storage and sequestration was higher than the business as usual scenario. The downward carbon sequestration trend could be reversed under environmentally sound planning. Therefore, the areas with a high potential of losing carbon storage under the business as usual scenario (i.e., expanding agricultural and urban land cover) and gaining carbon sequestration under the environmentally sound planning scenario (i.e., floating plants and agricultural lands) must exclusively be protected during the development of future land use/cover change policies. This ensemble of results could provide an integrated dynamic framework to the authorities for developing a systematic decision-making process by considering the spatiotemporal change on carbon storage and sequestration. The present study presents a one limitation of modeling carbon sequestration as the ecosystem of study area undergoes sever pressure for food needs and the lack of carbon data. The results can be used by environmental planners to improve and protect natural land covers, especially vegetation to protect the ecosystem services and their continuity. Finally, it is valuable to remember from this study that the carbon modeling in Manzala Lake would not only preserve the coastal ecosystems in the area but also generate valuable monetary returns on investment.

**Author contribution** All authors contributed equally to the study.

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**Data availability** All data generated or analyzed during this study are included in this published article and its supplementary information files.

**Declarations**

**Competing interests** The authors declare no competing interests.

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