Carbon sequestration potential of reclaimed desert soils in Egypt

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Summary

The objective of this study was to investigate the carbon storage potential of reclaimed soils under organic management. Agricultural soils are often mentioned as a potential carbon sink. However, until now the UNFCCC (United Nations Framework Convention on Climate Change) doesn't issue certified emission reductions (CERs) for carbon sequestration in soils.

This research focuses on carbon stock development of reclaimed desert soils in Egypt. The research was conducted on two farms owned by Sekem, one of which located 60 km north-east of Cairo, and the other one in the Sinai desert. Five agricultural fields of different ages (1-30 years in use) were selected and compared with the surrounding desert. In every field, representative soil samples were collected from 3 line transects, each consisting of 5 sample points. The samples were taken at three horizons; 0-10 cm, 10-30 cm and 30-50 cm, and tested for differences in physical (soil texture and bulk density), and chemical (acidity, salinity and organic carbon levels) properties.

The results show that reclaimed desert soils under organic management sequester carbon very rapidly in the first few years after land reclamation, but that this rate decreases after several years, following a logarithmic curve. The increase in soil carbon was first measured in the top soil (0-10 cm) and then in deeper soil layers. The bulk density of the top soil layer decreased at the same time.

The results show that in 30 years of organic agriculture, the soil carbon stock increased from 3,9 to 28,8-31,8 tons C/ha, a raise of ca 24,9-27,9 t C/ha. On average, the soil stored 0,9 t C/ha/y in these 30 years. Thus, an atmospheric CO_2 reduction of 3,2 tons CO_2-equivalents per ha and year had taken place.

It is rather unlikely that soil carbon sequestration will be approved by the UNFCCC on the short term as a methodology to mitigate the greenhouse effect. This is due to the fact that the permanency of carbon sequestration in soils is questionable. Issuing carbon credits to farmers in for instance underdeveloped dry land regions that sequester carbon in the soil could function as an incentive for sustainable farming. High organic matter levels reduce irrigation water needs and improve soil fertility, which may be helpful for combating droughts and food scarcity.

1 Introduction

Over the past few years, interest in climate change has grown exponentially. The world has realized that it is time to act. In February 2005, the Kyoto Protocol (an international agreement with the aim of reducing greenhouse gas emissions or GHG emissions) entered into force. For the first time in history, the international community obliged itself to react, and binding targets for the reduction of GHG emissions were set. The international authority managing these efforts is the UNFCCC. Part of the Kyoto Protocol is the introduction of a cap-and-trade method for GHG emissions: a cap is set for Annex 1 countries[1], which determines the amount of greenhouse gasses these countries are allowed to emit. With this method, a new tradable commodity was introduced: emission rights (also called carbon credits) that can be obtained by reducing emissions through the setting up of so called emission reduction projects. Theoretically, this method is the most cost-effective way to reduce GHG emissions.

One part of the Kyoto Protocol is the Clean Development Mechanism (CDM) which includes methodologies for emission reduction projects in developing countries. The approved methodologies for emission reduction projects mostly focus on renewable energy like wind, water and solar energy, although land use change (including deforestation and loss of soil carbon) accounts for more than 30% of the global GHG emissions (IPCC, 2007). As to agriculture, the CDM contains only few approved methodologies. Approved ones include co-digestion of manure and composting projects. Restoration of soil fertility or carbon content of soils is often mentioned but not yet included as an approved methodology.

The Kyoto Protocol will be reconsidered in December 2009 at the Copenhagen Conference, where emission reduction potentials for agriculture and land use will be on the agenda. In this respect, the content of this study is highly relevant.

Historically, agriculture and its related land use practices, like land shifting, cultivation and ploughing, have always been an important source of GHG emissions (IPCC, 2001). The soil stores about 1500 Pg of carbon in its upper horizons worldwide (0-100 cm) (Batjes, 1996; Batjes, 1998; Sombroek et al., 1993), which is more than the amount of carbon that can be found in vegetation or in the atmosphere (FAO, 2001). If an area of land is cleared and ploughed for agricultural purposes, soil organic matter (SOM) starts to decompose and SOM levels are decreasing. Commonly applied land use practices, such as the use of chemical fertilizers, accelerate this process and cause soil degradation.

On the other hand, agricultural soils are often mentioned as being a potential carbon sink that may be used to mitigate the global greenhouse effect that causes climate change (FAO, 2001; Lal, 2001; Lal, 2004). The function of a soil as carbon sink may be stimulated by land use practices that reduce decomposition rates of organic matter (like no-tillage) or by increasing the organic matter application rate by using organic fertilizers. The carbon content of a soil is a function of parent material, climate/environment, vegetation, topography, soil management and time. A soils' potential to function as a carbon sink is therefore highly dependent on the initial carbon stock of the soil, as well as and use practices. Compared to other soils, arid desert soils have a relatively high potential to act as a carbon sink, as their initial carbon stock is usually minimal.

In the case of Egypt, the carbon sequestration potential of arid soils is a relevant issue as land reclamation takes place at a large scale. Since the 1960s, expansion of the agricultural area through land reclamation is an important

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[1] Annex 1 countries: Industrialized countries

goal of national policies and market reforms (Chapin Metz, 1990). Since then, fruit and vegetable production has increased in line with objectives set by government authorities. This resulted in a shift from arable crops to horticultural products like tomatoes and potatoes, mainly cultivated for export purposes. Increases in yield are attributable to a raise in the number of larger, technologically more advanced farms in the reclaimed lands (Pautsch & Adbelrahman, 1998).

While conventional farming methods are still common practice, reclaimed lands are increasingly used for organic farming as well. The first bio-dynamic farm in Egypt, called Sekem, was started by Dr. Ibrahim Abouleish in 1977 in the eastern desert, 60 km north-east of Cairo. The land was reclaimed using flood irrigation and was fertilized with compost. Over the years, Sekem expanded in size and a mosaic of agricultural fields of different ages was gradually developed, providing an ideal environment for the measurement of the carbon sequestration of arid soils due to organic farming over time.

Carbon sequestration in reclaimed soils through the use of compost may become a methodology to generate carbon credits, which in turn may be an incentive for organic farming in desert regions like Egypt. Although the beneficial effects of compost on soil structure and hydro-physical properties of arid soils have been illustrated before (Wanas & Omran, 2006; Wahba, 2007; Wahba & Darwish), the potential carbon sink of reclaimed soils remains unknown.

The objective of this study was to investigate the development of reclaimed arid soils that are fertilized with organic compost. The main focus of the research was to determine the carbon sequestration potential of arid desert soils in Egypt.

2 Methods

2.1 Locations

Five arable fields of different ages (table 1) were selected on two different farms located in the eastern desert (Sekem Farm, near Bilbeis) and in the Sinai desert (Sinai farm, near the Suez Canal), both located in the north-eastern desert region of Egypt (figure 1-4). The agricultural fields are fertilized with compost that is produced on a composting facility where rice straw, water hyacinth, wood chips, organic waste, clay, chicken- and cow manure are used as input materials. The compost is applied during the preparation of the fields for the cropping season, which – in most cases – is twice a year (in May and September). During the preparation process, the fields are plowed (to a depth of 30 cm), and the compost is applied on and mixed with the soil. Average rainfall in the region is very limited, 24,8 mm/year, and is concentrated between November and March. Agriculture is therefore totally dependent on irrigation water coming from the Nile or from local ground water drillings. The average temperature in the region is 21.7 ˚C (annex 1).

The criteria used for plot selection were:

- The fields were not used for other activities before being taken into use for organic agriculture.
- The fields had to have a (more or less) stable rotation scheme where medical herbs and fodder crops or vegetables were cultivated.

Apart from the agricultural plots, undisturbed desert locations in the surroundings of the agricultural plots were selected. These desert locations were assumed to be representative of the initial desert soil, before the land was reclaimed and taken into cultivation. Geographical locations of the sample plots are displayed in figure 1 to 4.

Table 1. Age, crop rotation and location of selected plots.

Location	Nr of years in use	Crops cultivated at the field	GPS N	GPS E
Sekem Farm	0	Desert	30˚25.307'	31˚39.384'
Sinai Farm	0	Desert	30˚11.700'	31˚35.900'
Sinai Farm	1	Peanuts	30˚11.610'	31˚35.426'
Sekem Farm	4	Vegetables and medical herbs rotation	30˚22.834'	31˚39.468'
Sekem Farm	5	Vegetables and medical herbs rotation	30˚22.875'	31˚39.524'
Sekem Farm	30	Feed crops and medical herbs rotation	30˚25.118'	31˚38.174'
Sekem Farm	30	Feed crops and medical herbs rotation	30˚25.145'	31˚38.359'

Figure 1. Map of Egypt with the locations of the Sekem farm and the Sinai farm shown in yellow.

Figure 2. Close up of the northern region of Egypt with the two sample locations shown in yellow.

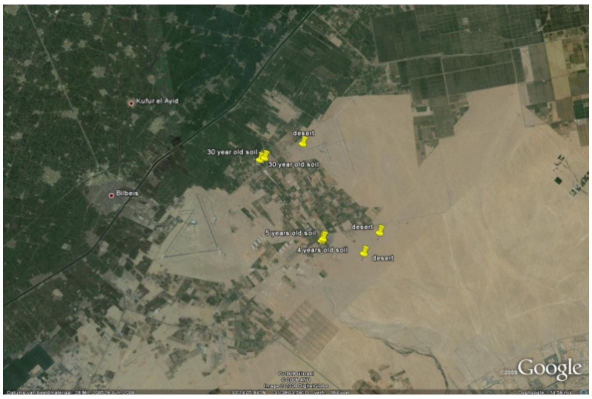


Figure 3. Close up of the Sekem farm and its surroundings.

Figure 4. Map of the Sekem farm and the sample locations shown in yellow.

2.2 Sample collection

The soil profile of every field was studied down to a depth of 50 cm. The fields were sampled in three line transects. Each transect consisted of 5 sample locations where samples were taken at three horizons (0-10 cm, 10-30 cm and 30-50 cm deep). From these horizons, the representative soil samples were air dried for chemical analyses. At the same sample locations and soil depths, bulk density samples were taken by hammering sample rings with a fixed volume into the soil. All samples were collected from the 20th of June 2009 to the 14th of July 2009.

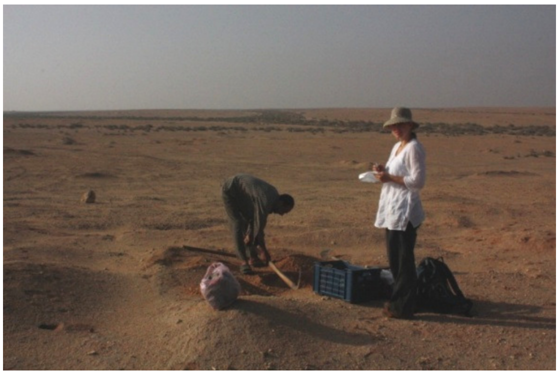


Figure 5. Sample collection in the desert adjacent to Sekem.

Figure 6. Sample collection in the 30-year-old fields of Sekem.

2.3 *Physical analyses*

The air dried soil samples were grinded and sieved over a 2 mm sieve. The total sample weight and the gravel weight > 2 mm were recorded. 50 g of each sample was weighted. Samples of corresponding depths within the same line transect were mixed and analyzed for physical and chemical properties.

The percentage of sand (0.06-2.0mm), silt (0.002-0.06mm), and clay (<0.002 mm) was measured in the lab by dropping speed after destroying micro-aggregates and organic matter. The bulk density samples were dried for 24 hours in a furnace at 105˚C. The bulk density was calculated by dividing the dry weight of the soil by the volume of the ring.

2.4 *Chemical analyses*

Twenty grams of the mixed soil samples were 1:5 diluted with distilled water and used for pH and EC measurements in threefold. As the soil contained a high level of (calcium) carbonates, the carbon content was measured by using wet oxidation (Walkley & Black, 1934). The organic matter content was calculated by multiplying organic carbon with 1,724.

2.5 *Data analyses*

To evaluate the carbon stocks of the different fields of different ages, it was necessary to convert carbon stock per volume of soil to carbon stock per specific weight of soil (Ellert et al., 2002). This method compensates for the change in bulk density of the soil over time. Calculation formulas used can be found in annex 3.

2.6 *Field histories*

Fertilizer regimes at Sekem include the application of compost that is produced on Sekem's own composting site. For all fields, the inputs (crop types, rotation scheme, fertilizer application, irrigation water use) and crop yields were inventoried by interviewing farm managers and studying documentation (annex 4). The information was used to estimate the total amount of organic carbon that had been applied on the different fields.

3 Results

3.1 Physical parameters

3.1.1 Soil texture

The soil texture in the different fields at the Sekem farm were comparable (classified as loamy sand), but significantly differed from the soil at the Sinai farm. The Sinai soil contained a smaller fraction of stones (>2 mm), silt and clay and a larger fraction of sand (Table 2) and was therefore classified as a sand soil. Due to the fact that the texture of soil can strongly influence soil carbon stocks, the data of the Sinai farm was analyzed separately.

*Table 2. Soil textures of the different fields (*average of two fields).*

Location	Years of compost application	% stones	s.d.	% sand	s.d.	% silt	s.d.	% clay	s.d.	n
Sinai	0	0%	1%	94%	1%	6%	1%	0%	0%	3
Sinai	1	2%	9%	93%	1%	6%	1%	0%	0%	9
Sekem	0	32%	13%	55%	8%	8%	4%	5%	4%	9
Sekem	4	36%	10%	53%	3%	10%	3%	1%	0%	9
Sekem	5	37%	10%	43%	1%	16%	1%	3%	1%	9
Sekem*	30	9%	9%	74%	5%	13%	5%	4%	4%	18

The bulk density at the depth of 0-10 cm was significantly affected by the agricultural practices (figure 7). In 30 years, bulk density decreased from 1,66 (± 0,16) to 1,42 kg/l (± 0,15), a decline of 14,5%. The bulk density at depths of 10-30 cm and 30-50 cm was not affected by the agricultural practices.

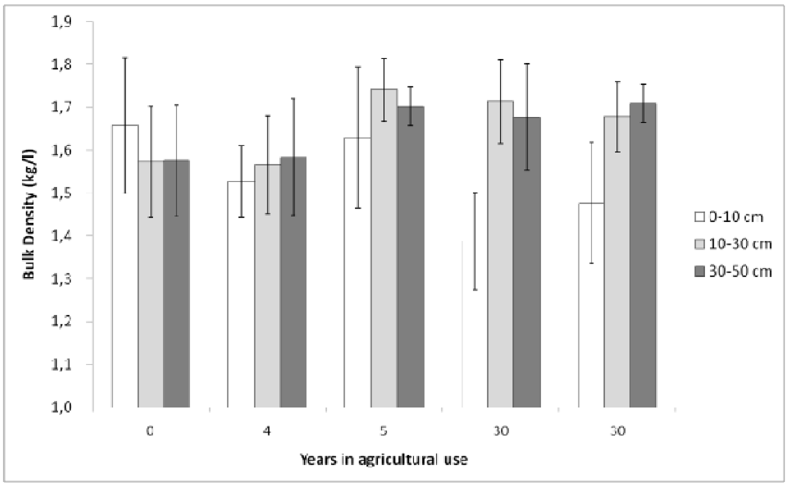


Figure 7. Bulk density development.

3.1.2 Soil surface

The soil surface of the desert near Sekem illustrates the low fertility and moisture level of this soil (figure 8). Plants are very scarce. Only in some lower areas desert shrubs are present. The 30 year old fields of Sekem were cultivated with alfalfa at the moment the samples were taken. The 4 year old field contained egg plants and tomato plants. The fields were heterogenic and many grasses and weeds were present at some places. On the 5 year old field, green beans were cultivated. On the Sinai soil, peanuts were cultivated when the sampling/collection of the samples took place. The applied compost could easily be detected at the soil surface, as it was not evenly distributed. The compost had floated towards lower areas of the field. Therefore, the compost could be easily found in some areas, whereas this was more difficult in some other parts of the field (figure 9).

Figure 8. Pictures of the soil surface of the fields at the Sekem location: desert (upper left), 4-year-old field (upper right), 5- year-old field (lower left), 30-year-old field (lower right).

Figure 9. The compost applied at the Sinai farm that has been cultivated for 1 year could easily be detected on the soil surface.

3.1.3 Soil profiles

The upper layer of the desert soil near Sekem contained many loose pebbles (figure 10). It was difficult to dig a hole in the desert soil, as the soil contained a hard stony layer at a depth of 10-25 cm. Below this stony layer, the soil contained less stones and was darker in color. Although it seemed that hardly anything could grow in this soil, tiny roots were found at a depth of 40 cm. Salt crystals were found at this depth as well.

The 4, 5 and 30 year old soil profiles displayed an A-horizon of 15 – 30 cm that was obviously darker in color than deeper soil layers. The thickness of this horizon was not homogeneous due to plowing activities. Over the entire soil profile, roots were found. At a depth of 40 cm precipitated calcium carbonate was found in the soil.

No horizons could be distinguished in the upper 50 cm of the Sinai desert soils.

Figure 10. Soil profiles of the desert soil (upper left) and the 4- (upper right), 5- (lower right) and 30-year-old soils (lower right) at the Sekem farm.

3.2 Chemical parameters

3.2.1 Organic carbon

The organic carbon content of the desert soils close to Sekem was 0,06% (0-10 cm) (table 3) whereas the fields on which compost had been applied for 4 and 5 years contained 0,58% and 0,79% of carbon in the upper 10 cm of soil and 0,39% and 0,31% in the 10-30 cm layer. The fields that had been in use for 30 years showed a carbon content of 0,99-1,39% in the 0-10 cm layer. The organic carbon level was 0,32-0,39% in the 10-30 cm layer of the two 30 year old fields. The carbon content of the deeper layer (30-50 cm) was not affected. The Sinai desert soil close to the farm had an organic carbon content of 0,05%, 0,01% and 0,01% in the layer of 0-10 cm, 10-30 cm and 30-50 cm deep, respectively. The one year old Sinai farm contained 0,24%, 0,02% and 0,01% of organic carbon in the same layers. This means that only the upper layer was affected by land use practices in the first year after reclamation.

Table 3. Organic carbon levels in the different fields.

Location	Years in use	% Organic Carbon 0-10 cm	s. d.	10-30 cm	s.d.	30-50 cm	s.d.	n per depth
Sekem	0	0,08%	0,01%	0,08%	0,00%	0,06%	0,01%	3
Sinai	0	0,05%	-	0,01%	-	0,01%	-	1
Sinai	1	0,24%	0,09%	0,02%	0,02%	0,01%	0,01%	3
Sekem	4	0,58%	0,01%	0,39%	0,06%	0,15%	0,05%	3
Sekem	5	0,79%	0,28%	0,31%	0,11%	0,06%	0,02%	3
Sekem	30	0,99%	0,25%	0,39%	0,20%	0,03%	0,06%	3
Sekem	30	1,39%	0,05%	0,32%	0,17%	0,08%	0,03%	3

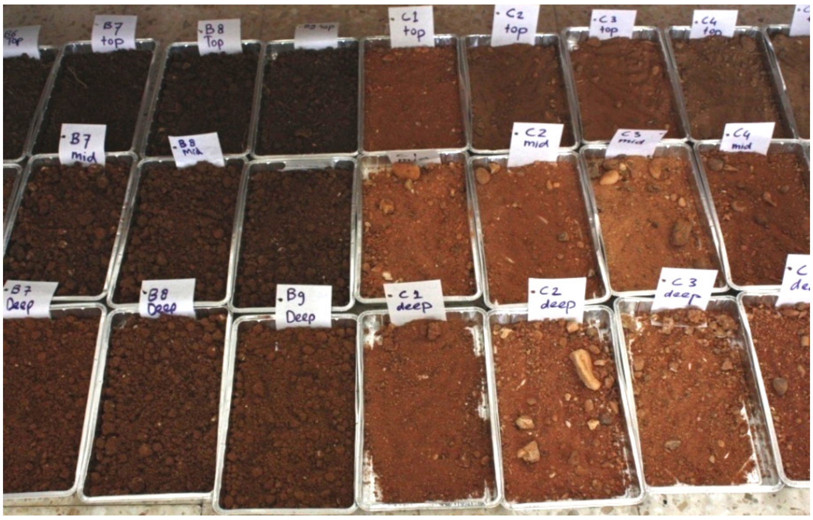


Figure 11. Drying soil samples of the 30 year old soil (left with code B) and the lighter colored desert soil (right with code C).

3.2.2 Soil carbon stocks

Like previously mentioned in the methodology section, the effect from land use practices on bulk density should be considered in the calculation of the soil carbon stocks. The bulk densities and soil mass of the desert soils were taken as a reference, because these soils were undisturbed (figure 7).

The soil in the desert near Sekem contained 3,9 tons C/ha in the upper 50 cm (figure 12). In the agricultural fields at Sekem farm, the carbon stocks were found to be significantly higher. The 4 and 5 year old fields contained 18,9 and 17,4 tons C/ha. The 30 year old fields contained 28,8 and 31,8 tons C/ha. In the Sinai desert, the virgin desert soil stored in total 1,6 tons C/ha in the upper 50 cm, whereas the one year old agricultural soils contained 5,7 tons C/ha (figure 13).

Most of the carbon in the agricultural soils was found in the upper 10 cm.

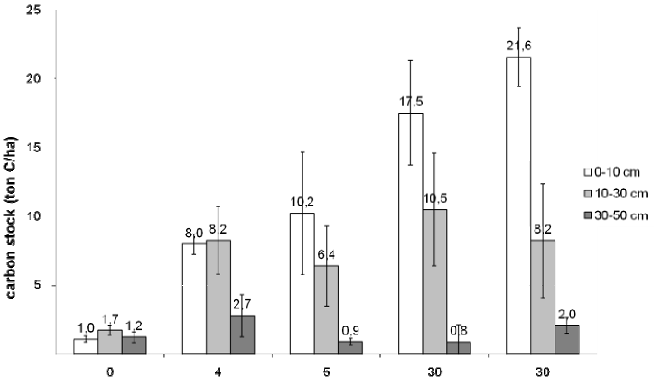


Figure 12. Soil carbon stocks of the different fields of the Sekem farm and the nearby desert.

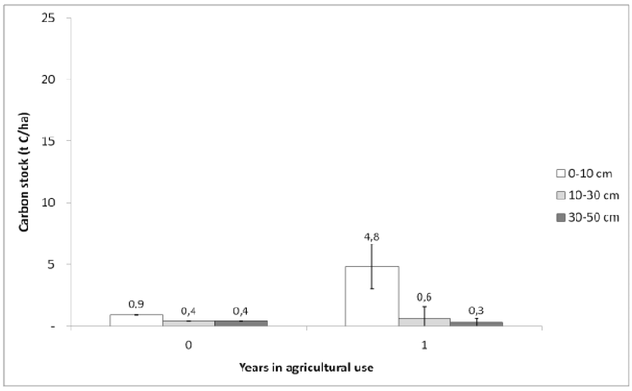


Figure 13. Soil carbon stocks of the Sinai farm and the nearby desert.

3.2.3 Salinity

The desert soil at the Sekem location showed a very high electric conductivity (around 4000 ppm) whereas the 4, 5 and 30 year old fields had an overall EC of between 240 and 750 ppm (table 4). The high salinity level of the desert soil was illustrated by the fact that mineral crystals were found during sample collection (figure 14). The soils in the Sinai desert contained less soluble salts and had an average EC of 250-340 ppm.

Figure 14. Mineral salt crystals found in the desert near Sekem farm.

Table 4. Salinity levels (Electric Conductivity ppm) in the different soil samples.

Location	Years in use	0-10 cm	s. d.	10-30 cm	s.d.	30-50 cm	s.d.	n per depth
Sinai	0	336	-	298	-	244	-	1
Sinai	1	281	80	314	126	364	200	3
Sekem	0	3.065	1.466	4.370	2.612	3.975	1.460	3
Sekem	4	757	32	421	109	608	265	3
Sekem	5	407	234	324	32	239	72	3
Sekem	30	579	41	644	86	521	78	3
Sekem	30	530	140	450	77	451	61	3

3.2.4 Acidity

The desert soil at the Sekem location was found to have an average pH of 7.9 (0-50 cm, table 5), whereas the agricultural fields were more alkaline with a pH of 8.5. The initial Sinai desert soil had an overall pH of 8.4, and the one year old soil was slightly more acid with a pH of 8.3.

Table 5. Acidity levels (pH) of the different soil samples.

Location	Years in use	0-10 cm	s. d.	10-30 cm	s.d.	30-50 cm	s.d.	n per depth
Sinai	0	8.7	-	8.2	-	8.3	-	1
Sinai	1	8.3	0.3	8.2	0.2	8.5	0.3	3
Sekem	0	7.7	0.2	7.9	0.3	7.9	0.3	3
Sekem	4	8.6	0.1	8.7	0.2	8.6	0.3	3
Sekem	5	8.4	0.4	8.4	0.1	8.5	0.1	3
Sekem	30	8.5	0.1	8.7	0.1	8.9	0.3	3
Sekem	30	8.2	0.1	8.3	0.1	8.5	0.2	3

3.3 Macro biology

Although no consistent methodology was used to investigate differences in macro biology, some soil invertebrates were encountered in the 30 year old fields during the fieldwork (figure 15). The invertebrates encountered belong to the genus *Lumbricus* (5 sightings) and *Gryllotalpidae* (3 sightings). In the other fields no soil macro fauna was encountered.

Figure 15. Soil invertebrates that were encountered in the 30 year old Sekem soils.

4 Conclusions

During this research soil samples of soils of different ages were collected. By this means the soil development due to land use practices could be reconstructed.

The desert soils around Sekem are generally slightly alkaline, have a very low carbon content and rather high salinity levels. The application of compost, green manures and irrigation, has lead to a change of the soil's properties over time. The soil properties at the Sinai location differed from those of the Sekem location, both physically and chemically.

The increase in soil carbon in the upper 50 cm amounted to 4,1 tons of C/ha after one year of farming at the Sinai farm (figure 16). The carbon levels during 5 years of organic farming at the Sekem farm also increased steeply with an average rate of 2,7-3,8 tons C/ha per year in the upper 50 cm of the soil. After the first 5 years till 30 years, the increase in carbon was lower with a rate of approximately 0,5 tons C/ha per year. The results indicate that the potential soil carbon sequestration resembles a logarithmic curve (figure 17), until equilibrium is reached between carbon application and decomposition by microorganisms. It seems that this equilibrium is not yet reached after 30 years of organic farming, but this cannot thoroughly be concluded by this study. Over a period of 30 years, the carbon stock increased from 3,9 to 28,8-31,8 tons C/ha in the upper 50 cm of the soil, a raise of 24,9-27,9 tons C/ha. If one were to imagine a linear relation, this would mean that each year 0,83-0,93 tons C/ha could be stored in the soil. This corresponds to a mitigation potential of 3,1-3,4 tons CO_2/ha/year.

The increase of carbon initially takes place in the upper 10 cm of the soil and shifts towards deeper soil layers after some years. In the first year of compost application the increase in carbon mainly takes place in the upper 10 cm. After 5 years of compost application, 68% of the carbon increase takes place in the upper layer and 35% in the 10-30 cm layer.

Although physical soil properties differ, the results of the two sampling sites were combined in figure 30 to illustrate the carbon stock development. To do so, a correction was made for the initial carbon stock of the Sinai desert soil, as this was lower than the initial carbon stock in the desert near Sekem. However, the method used is – as previously mentioned – not fully correct from a scientific point of view as the carbon sequestration potential in the soil at the Sekem farm is expected to be higher due to higher clay content.

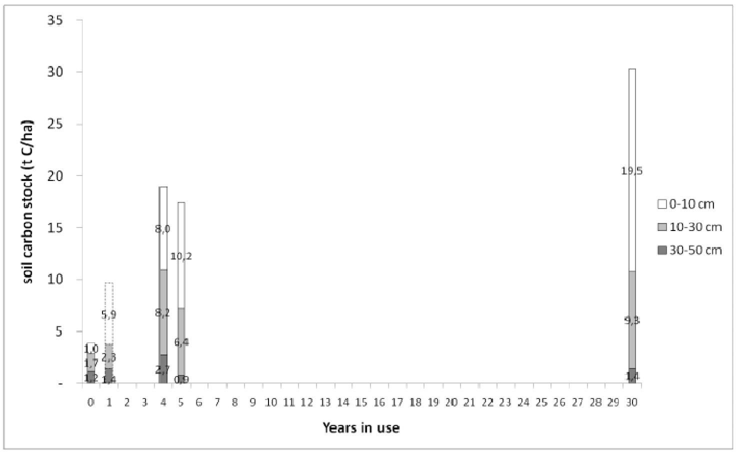


Figure 16. Measured carbon stocks of the different fields. The one year old field is located at the Sinai farm and indicated through dashed lines.

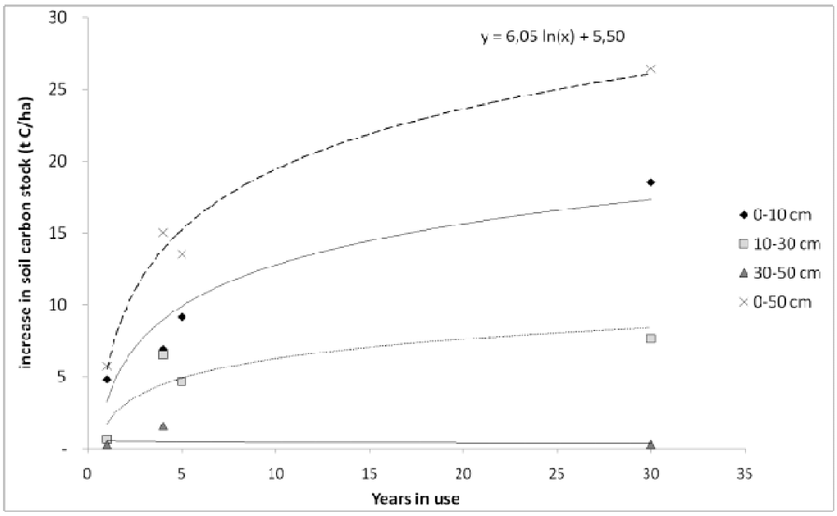
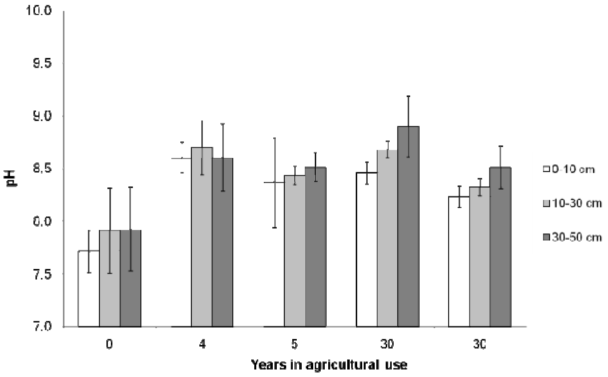


Figure 17. The increase in soil carbon mostly takes place in the upper 10 cm and follows a logarithmic curve.

The results also indicate that acidity and salinity are altered and stabilized more rapidly than carbon levels. Salinity levels dropped due to irrigation (figure 19). Especially during flood irrigation, the large surplus of irrigation water flushes the minerals to deeper soil layers. Salinity levels of the soil at the Sekem farm will not continuously decrease as the irrigation water is relatively saline. Sprinkler irrigation and drip irrigation systems were recently installed at the farm. Just like the quality of irrigation water, the transfer to other irrigation methods may affect future salinity levels of the soil, as this transfer affects the irrigation water surplus.

The organic practices affected the soil's acidity levels. Generally, the application of organic manures has a lowering effect on soil pH, because organic acids are released when compost or manure is broken down. However, the results show an increase from 7,9 to 8,5 (figure 18). The increase in pH is more often found in reclaimed desert soils and can be explained by insoluble salts (carbonates) present in irrigation water. They precipitate in the soil and cause the observed rise in alkalinity. High alkalinity levels may become problematic in agricultural soils, because they obstruct the crops' uptake of phosphates.



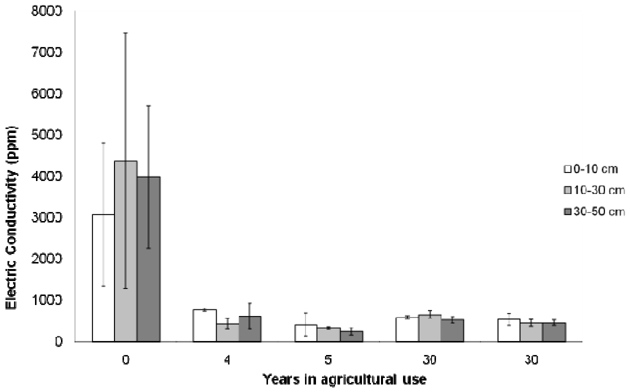


Figure 18. Acidity levels increase rapidly due to land use practices and then remain more or less stable.

Figure 19. Salinity levels of the soil decrease rapidly due to land use practices and then remain more or less stable.

5 Discussion

5.1 Carbon sequestration

Although soils contain the major terrestrial carbon reservoir and agriculture is one of the major causes of global greenhouse gas emissions (due to deforestation and land use practices), soil carbon restoration is not included as an approved methodology for emission reduction projects as part of the CDM of the Kyoto Protocol. Agricultural soils are often mentioned as a potential carbon sink. The studies that have so far been conducted to investigate the soils' carbon sequestration potential have a wide range in outcome (table 6). The carbon sequestration potential of a soil is highly dependent on the initial carbon stock of the soil, the parent material (chemical/physical properties), the climate/environment, the topography, as well as the vegetation/land use.

Comparing the result of this study with other studies, it can be concluded that this research found carbon sequestration rates in the first years of land reclamation to be much higher than the other studies. This can be explained by the fact that the initial carbon stock of the desert soil is extremely low and an increase of organic carbon levels can therefore be reached more easily.

The logarithmic curve that was found in this study is mentioned more often in literature (FAO, 2001).

The results of this study show that the carbon sequestration potential of reclaimed soils is significant. One might conclude that the effectiveness of compost applications regarding carbon stock development flattens over time, as the rate of carbon stock increase starts to slow down with a continuous application rate of compost. The flattening can be explained by the higher activity of micro- and macro fauna that are both more abundant in soils with higher carbon levels. This means in fact that if the same amount of compost is applied regularly and the slope of the curve is flattening, due to the decomposition and mineralization processes, more nutrients from the soil organic matter become available for plants.

Table 5. Results of former studies on soil carbon sequestration.

Author	Year	Initial Carbon Stock t C/ha	Soil carbon stock increase t C/ha/year	Method	Comment
Farage et al.,	2003	18	0,7	Application of farmyard manure (3 ton/ha) and plant residues (0,6 ton/ha)	Modeling study for dry land restoration in Kenya
Farage et al.,	2003	13	0,2-0,3	Application of farmyard manure, green manure, vermicompost and plant residues	Modeling study for dry land restoration in India
Rodale Institute	2005	Löss	1,14	Manure	Long term field experiment
Rodale Institute	2005	Löss	O,66	Legumes	Long term field experiment
This research	2009	0,9	2,7-3,8 in first years 0,5 in later years	Application of compost and green manures	Field measurements

According to a study carried out by FAO (2000), it is not a viable option that certified emission reductions (CERs) will be issued by the UNFCCC before the second commitment period (2012-2016), as the ability to measure carbon sequestration and the sustainability of the sequestration remains uncertain. Increasing the carbon level in soils mitigates the greenhouse effect in the short term, but in general soil organic matter is instable and can decompose rapidly once land management is changed. For the voluntary carbon market (VERs), incorporation of soil carbon development is more plausible. Currently, the Chicago Climate Exchange already incorporates measures to stimulate sustainable soil management of farmers by issuing carbon credits for conservation tillage (Chicago Climate Exchange, 2009). Organic soil management may also have other important beneficial effects (especially in Egypt), like reducing irrigation water use and improving soil fertility and soil productivity. Issuing carbon credits for soil carbon sequestration may therefore be an extra incentive for farmers to work on sustainable soil management.

This research shows that organic farming including compost application and use of green manures enables carbon sequestration. The average amount of compost applied on the 30 year old fields was 20 m^3/feddan per year (47,6 m^3/ha per year, table 7), which amounts to 2,7 tons of carbon (6,4 tons C/ha). Over a period of 30 years, the total supply of organic carbon on the fields summed up to 80,9 tons C/feddan (192,6 t C/ha), assuming equal compost properties over the years. Neglecting the fact that crop roots and crop residues are carbon suppliers, only 14% of the applied carbon in compost remained in the soil.

In terms of carbon sequestration, on average, 11,1 tons C/feddan is sequestered (26,4 t C/ha) in the soil in thirty years, which equals 40,7 tons of CO_2 equivalents/feddan (96,8 tons CO_2e/ha). If the carbon sequestration was equaled over the thirty years (linear instead of logarithmic relation), the carbon sequestration potential would amount to ca 1,4 kg CO_2 equivalents/feddan/year (ca 3,2 kg CO_2e/ha/year).

Table 6. Supply of carbon through compost and remaining amount per feddan and per hectare.

	per feddan	per hectare
Application of compost (m^3/year)	20,00	47,62
Supply of Organic carbon (tons/year)	2,70	6,42
Supply of Organic Carbon in 30 years (tons)	80,87	192,55
Initital carbon stock (tons)	1,64	3,90
Current carbon stock (tons)	12,73	30,30
C sequestration in 30 years (tons)	11,09	26,40
Organic carbon that remained after 30 years of continuous compost applications	14%	14%
C sequestered (tons/year)	0,37	0,88
CO_2 reduction potential (t CO2-eq/year)	1,36	3,23
CO_2 reduction after 30 years (t CO2-eq)	40,7	96,8

5.2 Remarks

This study measured the carbon stocks of several arable fields of different ages at a certain moment in time. The measurements were used to *reconstruct* carbon stock development over time, but carbon stocks from the fields were not measured at different moments. As shown in the field history reports (Annex 4), the land use practices of the fields used for this research were not explicitly equal, like it could have been organized in a long term field trial. There were some differences in the type of crops and rotation schemes of the fields, and in the irrigation methods that were used. Also, it is unlikely that the quality of applied compost has been exactly the same over the entire 30 years. However, we expect the results to give a good indication about the carbon storage potential of reclaimed desert soils. Due to the lack of real replicates of fields of a certain age (except for the 30 year old fields), certainty and range of carbon storage potential of reclaimed desert soils can be discussed.

The total soil carbon pool consists of different sub-pools with different characteristics. Shortly summarized one could say that some carbon is stable and some is labile depending on aggregate-constitution and chemical composition. Macro aggregates consist of micro aggregates that are bound together with fungal hyphae, roots and polysaccharides. These micro aggregates stabilize carbon. Soil management determines to a large extent whether micro and macro aggregates are present and therefore strongly influences soil carbon stability. The measurement of different soil carbon pools was not included in this research, as measuring techniques and interpretation of results are still problematic.

This research focused on the carbon sequestration potential of agricultural soils, however, the effects of organic matter content of soils on nitrous oxide emissions (N_2O) should also be considered. Nitrous oxide is a strong greenhouse gas with a global warming potential that is almost 300 times higher than CO_2. Former research has suggested a stimulating effect of organic matter on nitrous oxide emissions (Six et al., 2004; Venterea, 2005; Steinbach, 2006), due to enhanced water holding capacity of soils with high organic matter levels that provide a mixture of aerobe and anaerobe soil circumstances for soil microorganisms. A water filled pore space of 60% is optimal for nitrous oxide emissions (Linn et al., 1984). The possible effect of increased N_2O emissions may neutralize the mitigation potential of carbon sequestration.

In this study, the soil carbon content is measured by using the Walkley & Black method. This wet-oxidation method does not determine charcoal in the soil although significant amounts of charcoal were found in only the agricultural fields. No signs of onsite burning were found, which was confirmed by the farm managers and Dr.Ibrahim Abouleish (personal communication). Spontaneous combustion of compost windrows is an unwished phenomenon but occurs more often than realized (Rynk, 2000). Char formed within the windrows during the pyrolyzation process is the most likely source of the charcoal found in the agricultural soils.

5.3 Further research

In arid regions like Egypt, water use and soil development are important issues that are linked to carbon stocks of soils. The relation between compost application and water holding capacity of sandy soils is recognized in earlier studies (Wanas & Omran, 2006; Wahba, 2007; Wahba & Darwish, 2008) but not yet in relation with irrigation water requirements. A recent study of Wesseling et al. (2009) shows that organic matter amendments (in this study peat) seem a good solution to reduce irrigation water requirements. Also, Dr. Ibrahim Abouleish - the founder of Sekem -

mentioned that the fields get much more drought resistant over time (personal communication, 2009). The benefits of using compost as a way to adapt to climate change should therefore get more attention in further research.

This research focused on organic farms, but a comparable study is needed on conventional cropping systems in reclaimed desert soils to be able to show the potential benefits when farms change their practices towards more sustainable farming methods.

Moreover, it will be interesting to study effective soil management options for farmers to optimize soil carbon stock development.

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Annexes

Annex 1. Temperature and rainfall in the area]

	Average temperature	Average Rainfall
	˚C	Mm
January	13,8	5,1
February	15,2	3,8
March	17,4	3,7
April	21,4	1,5
May	24,7	1
June	27,3	0,2
July	27,9	0
August	27,9	0
September	26,3	0
October	23,7	1
November	19,1	2,5
December	15,1	5,7
year	21,65	24,5

Annex 2. Recent compost properties

Parameter	Unit	Value
Bulk Density	Kg/m3	624
Moisture content	%	21.8
Electric Conductivity (1:5)	dS/m	3.2
pH (1:5)		7.6
Total Organic Carbon	%	21.6
Total Organic Matter	%	37.4
Ash	%	62.6
Total Nitrogen	%	0.93
C/N ratio		23.3

Annex 3. Calculation formula for comparing carbon stocks per hectare with different bulk densities (Ellert et al., 2002).

$M_{C,\ equiv} = M_{C,\ surf} + M_{C,\ add}$

$M_{C,\ equiv}$ = C mass per unit area in an equivalent soil mass, tons/ha

$M_{C,\ surf}$ = C mass in surface layer(s), tons/ha

$M_{C,\ add}$ = C mass in additional layer required to attain equivalent soil mass, tons/ha

Carbon masses in successive soil layers are calculated using equation 2. The thickness of the additional soil layer (T_{add}) required attaining the equivalent soil mass is calculated as follows:

$T_{add} =(M_{soil,equiv} – M_{soil,\ surf}) \text{ x } 0{,}0001 \text{ ha/m}^2))/bd_{subsurface}$

T_{add} = thickness layer required to attain the equivalent soil mass, m

$M_{soil,equiv}$ = equivalent soil mass = mass in heaviest layers, tons/ha

$M_{soil,\ surf}$ = sum of soil mass in surface layer(s), tons /ha

$bd_{subsurface}$ = soil mass per sample volume of sub-surface layer, (tons /m^3)

Annex 4. Field histories

The desert soil around Sekem was sampled at three locations (figure 4). On each location, one line transect was made. One of these locations was a plain piece of desert that was used as a military area before. Close to these locations, some conventional agricultural fields, a chicken farm and Sekems composting facility were found, but the distance (>500 m) from the sample points was large enough to expect no influence.

Figure 20. The desert close to Sekem were the samples were collected.

The sample locations in the Sinai desert were located close to the farm (200 m) and a military base. Due to the finding of several military objects - probably remaining from the Six Day War in 1967 - , only one line transect was made and no further sampling was done outside the Sinai farm.

The one year old field at the Sinai farm was cultivated with peanuts during the sampling period. Before that, clover was grown. Fertilization was done by the application of compost, at a rate of 30 m^3 / feddan before each growing season. In total, 60 m^3 of compost per feddan (138 m^3/ha) has been applied since the field was taken into cultivation. A pivot irrigation installation with a radius of 800 m was irrigating the field continuously.

The 4 year old field at the Sekem farm was partly cultivated with tomatoes and partly with eggplant. The last vegetables were harvested just before the samples were collected. Due to a problem with soil nematodes, the yields were very low this year. The field was plowed and fertilized with compost (20 m^3/ feddan) before each growing

Figure 21. The 1 year old field at the Sinai farm was irrigated with a pivot running continuously.

Figure 22. The Sinai farm buildings.

season (47,6 m^3/ha). The field history couldn't fully be reconstructed due to a change in staff and missing records. However, from the existing records it is known that zucchini, peppers, tomatoes and eggplant were mostly rotated with basil, fennel or other medical herbs. The field was irrigated by drip irrigation. Crop residues were mostly removed and composted.

The 5 year old field was cultivated with green beans which had recently been harvested. Yields of this field were also low due to nematode problems. The field was plowed and compost application amounted to 20 m^3 /feddan (47,6 m^3/ha) before each growing season. During the winter season (from October 2008 to March 2009), the field was cultivated with chili peppers and chamomile. From August 2007 to August 2008, zucchini was grown on the fields. Before this, calendula and fennel were cultivated. The field was irrigated by drip irrigation. Crop residues were mostly removed and composted.

The 30 year old fields were cultivated with alfalfa which was sown in May 2009. The alfalfa will be harvested 7 times until 2012 and will be used as fodder for the cows at the farm. The total rotation scheme has a duration of 6 years and also includes chamomile, barley, silage (2x) and clover. Before each growing season the fields are plowed and fertilized with approximately 20 m^3/feddan. Crop residues were mostly removed and composted.

Figure 23. Compost application at a neighboring field at Sekem farm.

Figure 24. Drip irrigation of the vegetable fields at Sekem.

Figure 25. Alfalfa from the old fields are fed to the cows at the Sekem farm.

Figure 26. The 30 year old fields are irrigated by sprinklers.

Figure 27. Roundhouse, first Sekem building in 1977.

Figure 28. Roundhouse photographed from the same angle anno 2009.

Figure 29. Sekem field anno 1987.

Figure 30. The same field anno 2009.

Figure 31. Sekem field anno 1987.

Figure 32. The same field anno 2009.