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What is the potential for reducing atmospheric CO_2 levels through solar-desalinated irrigated vegetation of the Sahara and Arabian deserts?

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Abstract

9.8 gigatonnes of oil-equivalent fossil fuel were consumed in 2009 (BP, 2010). The negative aspects of anthropogenic climate change due to CO_2 emissions have been documented by Stern (2007). This thesis will consider a proposal to enhance the terrestrial carbon sinks, rather than focusing on reducing carbon emissions.

This thesis used existing data to investigate the potential of solar-desalinated water to irrigate the MENA region with a view to growing vegetation in the Sahara and Arabian deserts. The proposal being that this vegetation would lower atmospheric CO_2 by creating a net carbon sink. *Eucalyptus grandis x urophylla* was chosen as the species to model this proposal, due to its relatively well-researched growth rate and water requirement. It is acknowledged, however, that this species is non-indigenous to the MENA region and a monoculture of this fast-growing species, or any would not be recommended in reality.

The thesis calculated how much carbon could potentially be sequestered both in the vegetation and the soil of a *Eucalyptus grandis x urophylla* forest, on an estimated area of 8.4 million km^2 across the MENA deserts. Water required to irrigate this forest was calculated from existing research. The electricity demand to provide that water through desalination of seawater, mostly through reverse osmosis, and to supply the water to the trees by pumping it across the desert in pipes was then calculated. The thesis reviewed how much electricity could be generated using concentrating solar power in the MENA region and found there would be surplus energy generated, beyond that required for the desalination and irrigation processes. The area of land required for the parallel troughs or linear Fresnels used to provide the electricity was also calculated from the land use efficiency of the CSP units and the direct normal irradiation falling on an area of land. The costs, benefits and possible sources of income from this project were discussed.

Results from this thesis suggest that a forest of *Eucalyptus grandis x urophylla* occupying 8.4million km^2 of MENA deserts could be capable of sequestering 8 – 14.3$GtCyr^{-1}$ in the vegetation and upper-soil profile. Non-land-use-change anthropogenic carbon emissions are currently 8.7$Gtyr^{-1}$. The forest would require 7,560 – 8,400km^3 water yr^{-1} for irrigation, which would require 56,144 – 62,553TWh electricity yr^{-1} to desalinate. Electricity could be supplied by CSP units covering 324,532 – 579,194km^2. Major project costs included CSP units, RO plants and pipework. Benefits included ecosystem services, timber and carbon credits.

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Contents

Glossary

Aboveground plant respiration (R_a)	Respiration from aboveground parts of a plant. Contributes to total plant respiration.
Annual net primary production	The net annual accumulation of biomass assimilated into an ecosystem by the primary producers, by photosynthesis, after losses due to their respiration have been accounted for.
Arbuscular mycorrhizal fungi	Fungi that live in mutualistic symbiosis with green plants by invading their interior root cells and in essence vastly expanding their root systems, supplying the plants with nutrients such as phosphate in exchange for products of photosynthesis.
Autotroph	An organism that uses inorganic carbon to produce organic molecules such as carbohydrate.
Belowground plant respiration (R_b)	Respiration from belowground parts of a plant. Contributes both to total plant respiration and soil respiration.
Bureau international des poids et mesures	The International Bureau of Weights and Measures. An organisation that ensures the worldwide uniformity of measurements under the International System of Units.
C_3 plants	Plants that use C_3 photosynthesis, whereby CO_2 is first incorporated into a 3-carbon compound: 3-phosphoglycerate. Most plants use this type of photosynthesis.
C_4 plants	Plants that use C_4 photosynthesis, whereby CO_2 is first incorporated into the 4-carbon compounds malate and aspartate. C_4 plants have an advantage over C_3 plants in high temperature and drought conditions and they also suppress photorespiration.
Carbon capture and storage	The process of capturing CO_2, usually from power plant emissions, and storing it for example in underground geological formations or by reacting it with rocks to form carbonates.
Carbon dioxide	CO_2. Greenhouse gas. Part of the natural carbon cycle and released through combustion of fossil fuels.
Carbon dioxide equivalent	System that equates the Greenhouse gas potential of other gases such as methane to carbon dioxide.
Carbon negative	Processes that remove more atmospheric CO_2 than they emit. The processes may emit CO_2 but sequester more than they emit.
Carbon neutral	Processes that emit no net atmospheric CO_2. The processes may emit and sequester an equal amount.

Carbon sequestration	The removal of carbon from the atmosphere into other sinks such as the ocean, rocks, timber or soil, by natural or artificial processes.
Chemoautotroph	Autotroph that uses inorganic oxidation as an energy source and CO2 as a carbon source. For example nitrifying bacteria.
Chemoheterotroph	Heterotroph that uses inorganic oxidation as an energy source and organic carbon as a carbon source. For example animals.
Concentrating solar power	Form of renewable solar energy. Different to photovoltaics. CSP units use mirrors to focus sunlight onto absorber tubes to concentrate the heat. This heat is transferred to an electricity-producing turbine.
Crassulacean acid metabolism	Plants in which CO_2 is stored in a form that can be used at night. This enables the plants to close their stomata during the day to conserve moisture and open them at night enable extremely efficient water use.
Direct normal irradiation	A measure of how much solar energy an area of land receives. It is measured in KWh m^{-2} yr^{-1}.
Dry matter	Measurement of mass after the removal of water.
Ecosystem respiration (R_e)	Total respiration from an ecosystem including plant and soil.
Edaphic	General characteristics of the soil such as texture, drainage and pH.
Eucalyptus grandis* x *urophylla	Hybrid between *Eucalyptus grandis* and *Eucalyptus urophylla*
European Union Emissions Trading Scheme	CO_2 emissions trading scheme that operates within the European Union. The price of carbon is not fixed, but varies on the open market.
Gigatonne	One billion tonnes. Unit of weight – see Appendix A.
Gigawatt	Unit of power (the rate at which work is done) equal to 1,000 megawatts.
Gigawatt-hour	One million kWh. Unit of energy – see Appendix A.
Greenhouse Gas	Atmospheric gases that enhance the Earth's ability to hold heat and hence cause average global temperatures to rise.
Gross Primary Production / Productivity	The net annual accumulation of biomass assimilated into an ecosystem by the primary producers, by photosynthesis, without accounting for losses due to respiration.
Heterotroph	An organism that uses organic carbon as an energy source.

High Voltage Direct Current	An electricity transmission system that suffers fewer transmission losses than alternating current systems over a long distance.
Joule	Unit of energy – see Appendix A.
Kilowatt	Unit of power (the rate at which work is done) equal to 1,000 watts.
Kilowatt-hour	Unit of energy – see Appendix A.
Land Use Efficiency	Solar Electric Efficiency x Land Use Factor (expressed as a percentage)
Land Use Factor	The Total Land Area Required with CSP units / Aperture Area of Reflectors (expressed as a percentage)
Mean annual biomass increment	A measure of the average annual increase in biomass in a forest, often a planted forest. Often measured for a number of years and then averaged. Used to calculation forestry plantation timber yields.
Megagram	One tonne – see Appendix A.
Megajoule	Unit of energy = 0.277 kWh – see Appendix A.
Megawatt	Unit of power (the rate at which work is done) equal to 1,000 kilowatts.
Megapascal	1 N mm^{-2}
MENA deserts	Collective term for the Sahara and Arabian Deserts (The Middle East and north African deserts).
Microbial respiration (R_m)	Respiration from microorganisms. Contributes to total soil respiration.
Multi-effect desalination	A type of desalination that uses thermal distillation as opposed to membrane filtration.
Net Ecosystem Production / Productivity	The net primary production is equal to the ANPP minus the annual heterotrophic respiration.
Non-land-use-change anthropogenic carbon emissions	Causes of emissions of carbon from CO_2 by human activities such as burning fossil fuels and manufacturing cement, as opposed to land-use-change activities such as ploughing soil and burning forests. This does not include other GHGs.
Parts per million	Measure of relative proportions. In the case of atmospheric gases for example 390 ppm CO_2 is equal to 0.039%

Penman-Monteith method / equation	Method to calculate evapotranspiration rate based on inputs of mean temperature, wind speed, relative humidity, and solar radiation.
Permanent wilting point	This is the soil water content point beyond which a wilting plant in dry conditions cannot recover its turgidity after water is made available again. It is the water content at 1500 J kg^{-1} of suction pressure.
Petagram	One Gigatonne – see Appendix A.
Photoautotroph	Autotroph that uses light as an energy source and CO2 as a carbon source. For example green plants.
Photoheterotroph	Heterotroph that uses light as an energy source and organic carbon as a carbon source. For example some purple bacteria.
Photorespiration	An erroneous process in the Calvin cycle of photosynthesis when O_2 replaces CO_2 due to C_3 plants closing their stomata to reduce water loss.
Plant respiration (Autotrophic respiration) (R_p)	Total plant respiration composed of aboveground and belowground plant respiration.
Relative humidity	A measure of the amount of water vapour in a gaseous mixture of water vapour and air. Expressed as a percentage.
Reverse osmosis	A method of desalination. Pressure is applied to seawater on one side of a selective filtration member causing fresh water (the solvent) to pass through retaining the salt (solute) on the original side. This movement of solvent from an area of high solute concentration to an area of low solute concentration is the opposite of naturally occurring osmosis without the application of pressure.
Sequestered carbon	Carbon that moves from the atmosphere into other sinks such as the ocean, rocks, timber or soil.
Soil inorganic carbon	Soil carbon from inorganic sources. Can be lithogenic (inherited from parent material of the soil) or pedogenic (formed through the dissolution and precipitation of carbonate parent material).
Soil organic carbon	Soil carbon from organic sources: living organisms.
Soil respiration (Rs)	Total soil respiration composed of belowground plant respiration and microbial respiration.
Solar electric efficiency	SEE is the Annual Direct Irradiance on Aperture of a CSP unit / Annual Net Power Generation (expressed as a percentage)

Système international d'unités	International System of Units. The official system of units of almost every country. Based on seven base units: metre, kilogram, second, ampere, Kelvin, mole, candela
Terawatt	Unit of power (the rate at which work is done) equal to 1,000 gigawatts.
Terawatt-hour	One million MWh. Unit of energy – see Appendix A.
Total belowground carbon allocation	Proportion of carbon sequestered by primary producers during photosynthesis that is allocated to the root system of the plant.
Trans-Mediterranean renewable energy cooperation	A voluntary organisation initiated by the German association of the Club of Rome that campaigns for co-operation in energy supply from renewables between EU-MENA nations and particularly the transference of electricity via HVDC cables from MENA to Europe.
Transpiration efficiency	The ratio of the mass of DM produced by a primary producer to the mass of water transpired. TE = g dry matter (DM) l-1 water.
Transpiration ratio	Reciprocal of transpiration efficiency. TR = litres water transpired kg-1 DM produced.
Watt	Unit of power (the rate at which work is done) equal to 1 m^2 kg s^{-3}.

List of Abbreviations

AMF	Arbuscular mycorrhizal fungi
ANPP	Annual Net Primary Production
AQUA-CSP	Concentrating Solar Power for Seawater Desalination
BIPM	Bureau international des poids et mesures (The International Bureau of Weights and Measures)
°C	Degrees Centigrade
C	Carbon
CAM	Crassulacean acid metabolism
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CSP	Concentrating Solar Power
CCS	Carbon Capture and Storage
DLR	Deutsches Zentrum für Luft und Raumfahrt (German Aerospace Centre)
DM	Dry Matter
DNI	Direct Normal Irradiation
E. grandis* x *urophylla	*Eucalyptus grandis* x *urophylla*
EPA	(United States) Environmental Protection Agency
ESRL	Earth System Research Laboratory
ESRLWT	Earth System Research Laboratory Web Team
EU	European Union
EU ETS	European Union Emissions Trading Scheme
EU-MENA	European Union, Middle East and North Africa
FAO	Food and Agriculture Organization of the United Nations
GDP	Gross Domestic Product
GDPPP	Gross Domestic Product per Person
GGW	Great Green Wall (Grande Muraille Verte)

GHG	Greenhouse Gas
GMR	Great Manmade River
GPP	Gross Primary Production/Productivity
Gt	Gigatonne = 10^9 tonnes
GWh	Gigawatt-hour
Ha	Hectare (10,000m^2)
HVDC	High Voltage Direct Current
IMF	International Monetary Fund
IPCC	The International Panel on Climate Change
J	Joule
kWh	Kilowatt-hour
LUF	Land Use Factor
LUE	Land Use Efficiency
MA	Millennium Ecosystem Assessment
MAI	Mean Annual Biomass Increment
MEA	Millennium ecosystem assessment
MED	Multi-effect desalination
MED-CSP	Concentrating Solar Power for the Mediterranean Region
MENA	Middle East and North Africa
Mg	Megagram = 1 tonne
MJ	Megajoule
MPa	Megapascal
MW	Megawatt
NEP	Net Ecosystem Production/Productivity
NGO	Non Governmental Organisation
NPP	Net Primary Production/Productivity
Pg	Petagram = 10^{12} g = 10^9 tonnes = 1 Gigatonne

PPIGW	Panel on Policy Implications of Greenhouse Warming
ppm	Parts per million
(θ_{pwp})	Permanent wilting point
R_a	Aboveground plant respiration
R_b	Belowground plant respiration
R_e	Ecosystem respiration
RH	Relative Humidity
R_m	Microbial respiration
RO	Reverse Osmosis
ROI	Return on Investment
R_p	Plant respiration (Autotrophic respiration)
R_s	Soil respiration
SEE	Solar Electric Efficiency
SOC	Soil Organic Carbon
SI	Système international d'unités (International System of Units)
SIC	Soil Inorganic Carbon
SWRO	Seawater Reverse Osmosis
T	Tonne
TBCA	Total belowground carbon allocation
TE	Transpiration Efficiency
TEEB	The Economics of Ecosystems and Biodiversity
TRANS-CSP	Trans-Mediterranean Interconnection for Concentrating Solar Power
TR	Transpiration ratio
TREC	Trans-Mediterranean Renewable Energy Cooperation
TWh	Terawatt-hour
UK	UK United Kingdom of Great Britain and Northern Ireland
UN	United Nations

UNEP	United Nations Environment Programme
US$	United States Dollars
USDA	United States Department of Agriculture
USDC	United States Department of Commerce
Veg$^{n.}$	Vegetation
Yr	Year

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Chapter 1 Introduction

The purpose of this thesis is to estimate how much carbon could be sequestered annually in the Sahara and Arabian deserts if those deserts were irrigated with seawater that had been desalinated using CSP, allowing the establishment of vegetation and formation of soil. Successful sequestration of carbon in this manner would constitute climate change mitigation, defined by the IPCC working group as ‘An anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases.’ (Metz et al., 2001, p.716). The research in this thesis is restricted to carbon from CO_2 emissions and does not consider other GHGs.

1.1 The Global Carbon Cycle

To understand the global carbon cycle one must relate GtC to ppm atmospheric CO_2. 1ppm CO_2 corresponds to 2.12GtC (ESRL, 2009). The pre-industrial atmospheric CO_2 level of 280ppm is equivalent to 593.6GtC and the present level of 390ppm (ESRL, 2010) equivalent to 826.8GtC. However, as this 110ppm increase in atmospheric CO_2 is only equivalent to 233.2GtC, it is clear that not all the carbon emitted by human industrialisation has remained in the atmosphere. Indeed, in addition to the 500GtC emitted due to industrialisation, there are estimates of a further 156GtC of emissions due to land use change from 1850 to 2005 (Houghton, 2008). So of the total emissions of 656GtC since industrialisation, only 233.2GtC have remained in the atmosphere.

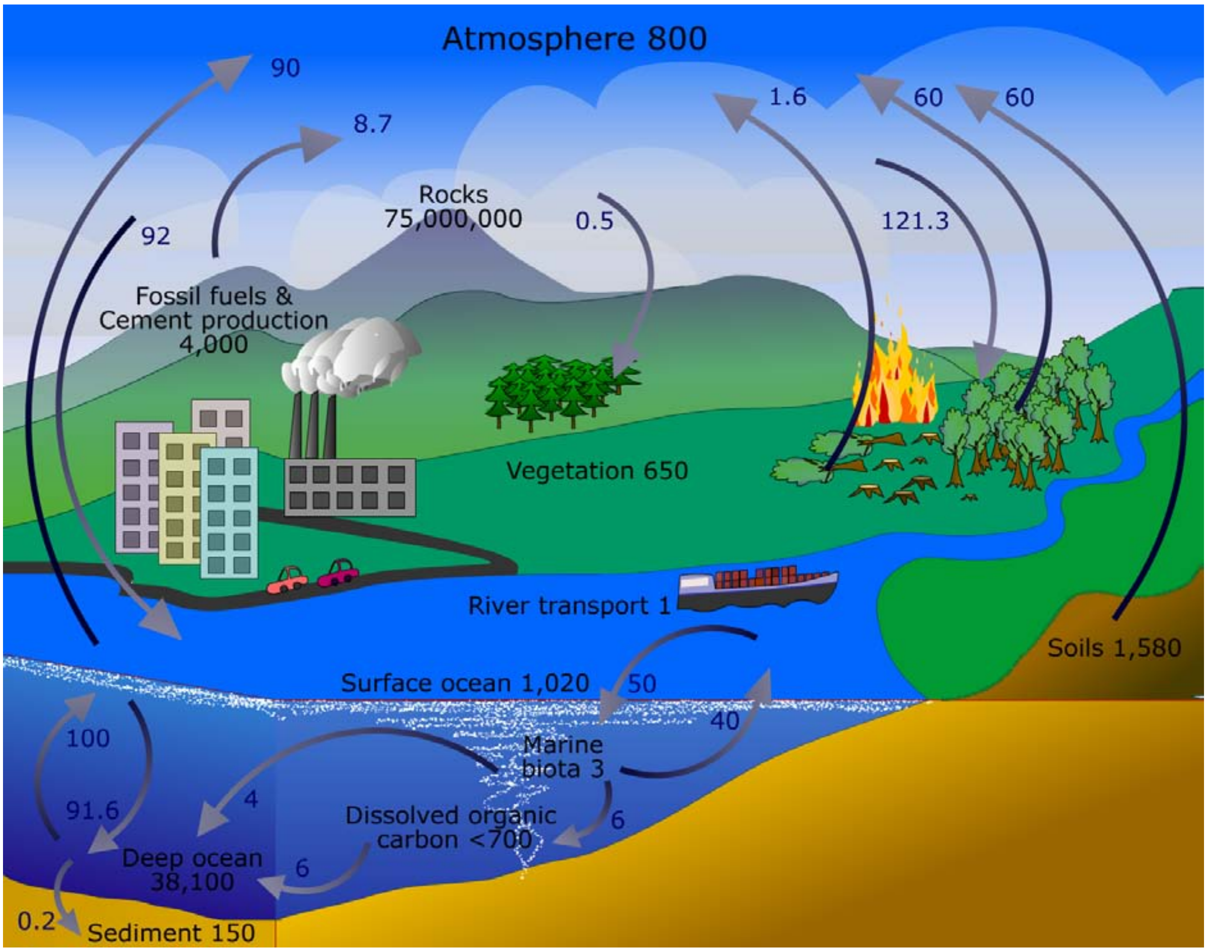

Figure 1.1 Global carbon cycle – figures are gigatonnes of carbon.

Sources: (Luo & Zhou, 2006, p.23) and (NASA, 2001) amended and redrawn with data from (Le Quéré et al., 2009).

Reducing fossil fuel use cannot directly lower atmospheric CO_2. Robust terrestrial carbon sinks are increasingly viewed as an essential part of climate change mitigation (Dudley et al., 2010). Continued environmental degradation is expected to reduce the land sinks' capacity to absorb atmospheric CO_2 as rising levels reduce the fertilisation effect of CO_2 and a decreasing ocean carbonate concentration reduces its capacity to buffer CO_2 (Le Quéré et al., 2009, p.3). However, due to the insufficient CO_2 reduction targets in the Copenhagen Accord (Rogelj et al., 2010), even fully restored, it is likely that the previously damaged environments will not have the potential to absorb enough CO_2 to prevent a 2°C rise in global temperatures by 2050 (Rogelj et al., 2010) with associated catastrophic environmental consequences predicted such as melting ice sheets, rainforest dieback and natural vegetation changing from a CO_2 sink to a source more likely to occur (Stern, 2007, p.vi).

Hansen et al. (2008) have suggested that a 'safe level' of atmospheric CO_2 is 350ppm. This is equivalent to 84.8GtC. To return to 350ppm, a net reduction in atmospheric carbon must be achieved each year. This will involve not only preventing or sequestering any further annual emissions of carbon, but also sequestering additional carbon from the atmosphere. The net flow between the component parts of the carbon cycle as shown in Figure 1.1 is dynamic, difficult to model and subject to large error bars (Le Quéré et al., 2009). This thesis will aim to estimate the carbon that could be sequestered on an annual basis in the vegetation and soil of a land sink that currently has very low soil organic carbon (SOC) and even less in the vegetation (Table 3.1) – the MENA deserts – and relate this to current 8.7GtC emitted through non-land-use-change anthropogenic activities in 2008 (Le Quéré et al., 2009). A visual comparison of non-land-use-change anthropogenic carbon emissions and volumes of timber that contain the same amount of carbon is given in Appendix C.

1.2 The MENA deserts

The thesis proposes irrigating the hyperarid MENA deserts. The Sahara Desert occupies approximately 9,100,000 km^2 and the Arabian Desert 2,330,000 km^2 (Butterfield et al., 2003, p.1423 and 81) totalling 11,430,000 km^2 of land: 7.7% of the world's land area (CIA, 2010d).

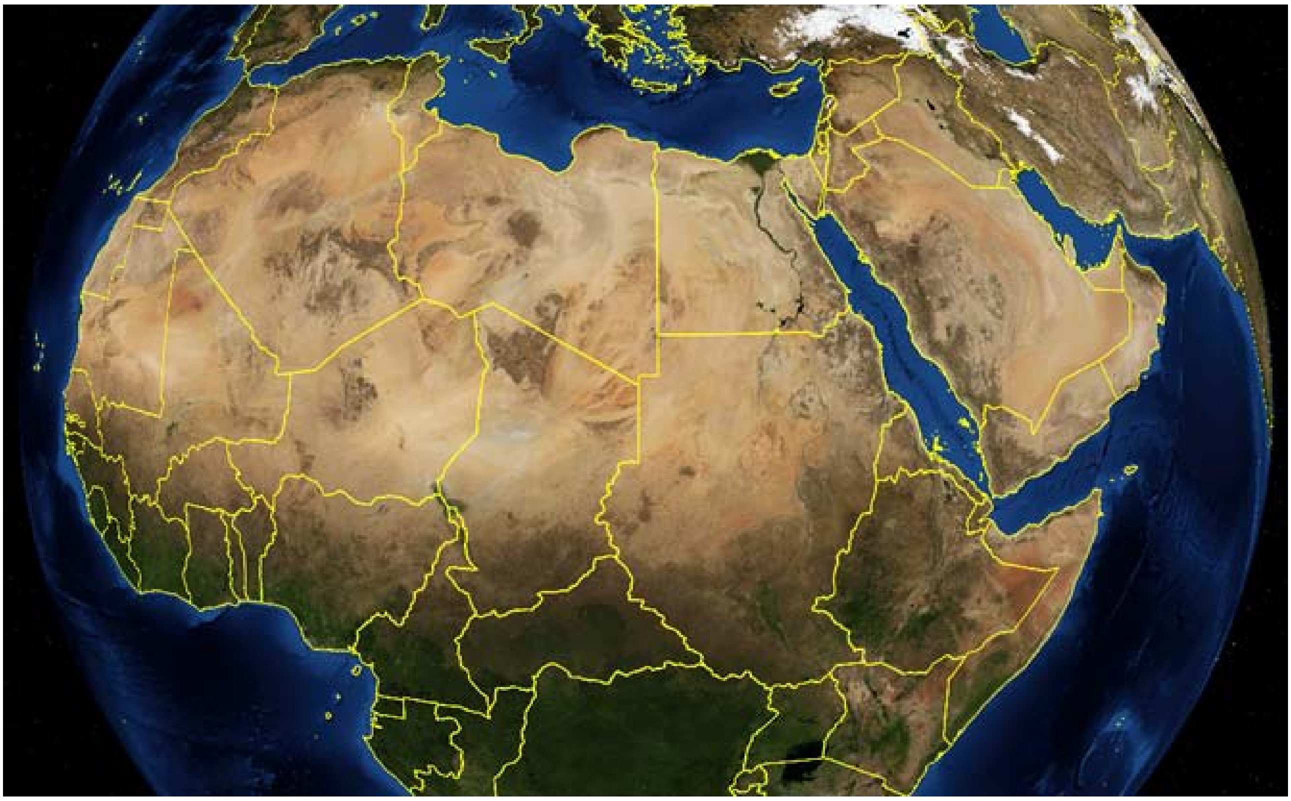

Figure 1.2 The Sahara and Arabian Deserts

Source: NASA World Wind (2007)

If this amount of land could be transformed into a carbon sink it could make substantial impacts in the level of atmospheric CO_2. Of course not all of this land will be available as some will be needed for infrastructure, some will be inaccessible and some will be occupied either temporarily or permanently.

1.3 Methodology

The question "What is the potential for reducing atmospheric CO_2 levels through solar-desalinated irrigated vegetation of the Sahara and Arabian deserts?" was answered using pre-existing data. The subject matter was too broad and the study period too short to generate primary data. To answer the main question the following sub-questions were researched:

1. How much carbon can primary producers sequester, how efficiently and consuming how much water?
2. What role does soil play in the carbon cycle and how much carbon can it sequester?
3. What kind of desalination technology would be suitable to provide the water to irrigate the primary producers, and what is the energy requirement?
4. How much electricity could be generated using CSP in the MENA region?
5. What infrastructure will be needed and what are the costs and benefits?

The purpose of questions 1 and 2 was to calculate how much carbon could be sequestered $yr^{-1}ha^{-1}$ in vegetation and soil for a known quantity of water in a tropical location. Question 3 aimed to calculate how much electricity would be required to provide this water, and question 4 to calculate how much land devoted to CSP in the MENA deserts would be needed to produce this electricity. Finally, the aim of question 5 was to examine the costs and benefits of implementing this project.

Most data was collected by online research. Major fields included forestry, soil science, desalination technology and concentrating solar power. Other research fields included, ecosystem services, carbon markets and economics. Data was correlated, calculated and used to produce graphs using Microsoft Excel 2000 (Microsoft Corporation, 2000). Illustrations were created using Google Earth 6 (Google, 2010), Google Sketchup 8 (Google, 2010), NASA WorldWind 1.4.0.0 (NASA, 2007), Inkscape 0.48 (Inkscape, 2010) and GIMP 2.6 (GIMP, 2010).

1.4 Thesis outline

- **Chapter 2** investigated the rate at which plants can sequester atmospheric CO_2 into carbon, and the amount of water they require to do so. The chapter estimated the amount of water required to irrigate vegetation in the MENA deserts and the potential sequestration of atmospheric carbon this could allow.
- **Chapter 3** examined the carbon stored in the soils of various ecosystems, and the role of soils in the carbon cycle. The chapter estimated the amount of carbon that could be stored in the MENA deserts if they transitioned from a desert to a forest ecosystem.
- **Chapter 4** discussed various desalination technologies and the associated energy requirements. The amount of desalinated water required to irrigate the MENA deserts was estimated, taking into consideration that a predicted future water shortage in the nations of the MENA region must also be bridged. The chapter estimated the amount of electricity required to desalinate this water.
- **Chapter 5** reviewed the Desertec concept (Wolff, 2010) and the work that the foundation commissioned the Deutsches Zentrum für Luft und Raumfahrt (German Aerospace Centre) (DLR) to undertake to assess the potential of the MENA region to generate electricity by CSP. Chapter 5 related this to the electricity needed to desalinate seawater to irrigate the MENA deserts, and considered other electricity requirements in the MENA region and sub-Saharan Africa.
- **Chapter 6** revised the calculations performed throughout this thesis based on a known size of land to be set-aside for CSP units and a re-estimated amount of land available for irrigation.
- **Chapter 7** considered the infrastructure costs (CSP units, RO plants and pipework) of a project to irrigate the MENA deserts, the benefits in terms of ecosystem services and sources of income.
- **Chapter 8** the conclusions, summarised the thesis, discussing any limitations and ideas for future research.

Chapter 2 to Chapter 5 each end with a box containing key data. This data will be used to perform calculations throughout this thesis based on a land area of 11,430,000 km^2 of desert. In Chapter 6 these calculations will be revised once the actual land area available to support vegetation is ascertained.

1.5 Literature review

This thesis used secondary data and as such the literature review will be embedded within the chapters that follow: particularly Chapter 2 – Chapter 5. However the following sources deserve particular mention:

The paper *Irrigated afforestation of the Sahara and Australian Outback to end global warming* (Ornstein et al., 2009) provided background reading and lead to authors of other papers. In particular the work of Stape (2002) and Stape et al. (2004) on clonal Eucalyptus was important in Chapter 2.

The book *Soil Respiration and the Environment* (Luo and Zhou, 2006) was a good source of data related to soil carbon and provided many leads to authors in this field. This helped particularly with Chapter 3

Most importantly, this thesis referred to studies performed by the DLR during that organisation's research into the DESERTEC concept. Two studies, *MED-CSP* and *TRANS-CSP* estimated the potential of the MENA deserts to produce electricity, much for export to Europe, (Trieb et al., 2005; Trieb et al., 2006). The third study, *AQUA-CSP*, investigated using CSP desalination to eliminate the MENA region's predicted future freshwater deficit (Trieb et al., 2007). These studies provided a great deal of primary research material for Chapter 4 and Chapter 5.

1.5.1 Data quality

The reliance on secondary data leads to limitations. It was difficult to find data related to the water requirements of plants, particularly via irrigation and under different RH conditions. The thesis was restricted to the species that had been previously studied, including the widespread forestry tree *Eucalyptus grandis x urophylla*, of which water requirements have been documented. These issues will be investigated throughout the thesis. The quality of the data sources used, particularly those that supplied input to the calculations is summarised in Appendix B.

1.6 Aim

This thesis aims to provide an early indication of whether it is feasible to irrigate the Sahara and Arabian deserts and establish vegetation capable of sequestering atmospheric carbon using existing technologies such as concentrating solar power and reverse osmosis. This thesis aims to provide the theoretical background research that will lead to a range of practical studies to test the accuracy of the estimates made. The ultimate aim of the thesis is to promote the use of renewable energy to provide freshwater for desert restoration projects within the MENA region and beyond, leading to the development of terrestrial carbon sinks capable of sequestrating large amount of atmospheric CO_2 in both vegetation and soil.

Chapter 2 Vegetation

2.1 Introduction

This chapter will investigate the rate at which primary producers can convert atmospheric CO_2 into carbon, and how much water they require to do so. It will estimate the amount of water that would be required to irrigate the MENA deserts and the potential sequestration of atmospheric carbon this could allow.

2.2 Photosynthesis

Photosynthesis is the process whereby green plants fix atmospheric CO_2 and water into carbohydrate biomass. The overall equation is:

$$6CO_2 + 6H_2O + \text{Energy} \rightarrow C_6H_{12}O_6 + 6O_2$$

Equation 2.1 Photosynthesis

(Miyamoto, 1997)

2.2.1 Maximum amount of carbon sequestered

There are a number of steps within the photosynthetic process from light capture to carbohydrate manufacture, each with associated energy losses. Furthermore not all the light that reaches earth can be used for photosynthesis. The theoretical maximum rate of conversion of solar energy to biomass efficiency is estimated at 4.6% and 6% for C_3 and C_4 plants respectively (Zhu et al., 2008). The majority of the world's plant species are C_3 plants and use C_3 photosynthesis, whereby CO_2 is first incorporated into the 3-carbon compound 3-phosphoglycerate. C_4 plants use C_4 photosynthesis, whereby CO_2 is first incorporated into a 4-carbon compounds malate and aspartate. C_4 plants have advantages over C_3 plants in high temperature and drought conditions due to their efficient water use and suppression of photorespiration (a process whereby O_2 is erroneously substituted for CO_2 during photosynthesis) (Heldt and Heldt, 2005, pp.222-223).

477Kj (0.1325kWh) of energy are stored in plant biomass for every mole of CO_2 fixed during photosynthesis (Miyamoto, 1997). As parts of the MENA region receive an average of 2800KWh $m^{-2}yr^{-1}$ solar radiation (Trieb et al., 2009, p.3) a C_3 plant growing here could theoretically fix a maximum of 117tC $ha^{-1}yr^{-1}$ and a C_4 plant a maximum of 152tC $ha^{-1}yr^{-1}$. Of course this is not a linear process but part of a dynamic system of gaseous fluxes from plants and soil. This will be investigated in Chapter 3.

One mole of CO_2 contains 12g of carbon.

It takes 0.1325KWh to fix 12g of carbon.

In a location receiving 2800kWh solar radiation $m^{-2}yr^{-1}$ and a solar energy to biomass efficiency of 4.6% a C3 plant could fix:

2800/0.1325*4.6%*12 g = 11,665 gC $m^{-2}yr^{-1}$ = **117tC $ha^{-1}yr^{-1}$.**

In a location receiving 2800kWh solar radiation $m^{-2}yr^{-1}$ and a solar energy to biomass efficiency of 4.6% a C4 plant could fix:

2800/0.1325*6%*12 g = 15,215gC $m^{-2}yr^{-1}$ = **152tC $ha^{-1}yr^{-1}$.**

Box 2.1 Maximum theoretical rate of carbon fixation in C_3 and C_4 plants tC ha^{-1} yr^{-1}

However this is the maximum theoretical solar energy conversion. The maximum observed was 2.4% and about 3.7% for C_3 and C_4 crops across a full growing season

(Zhu et al., 2008). This would result in 60.86 and 93.82tC ha^{-1} yr^{-1} being sequestered, but only if the growing season or seasons lasted a full year. The actual observed biomass over a growing season for the C_4 plant in question was 80tDM standing crop ha^{-1} with an annual NPP of 99t ha^{-1} DM (Zhu et al., 2008). At 45%C, the figure reported for agricultural material (BFIN, n.d.), would suggest a sequestration rate of 36 – 44tC ha^{-1}yr^{-1}. The plant in question was *Echinochloa Polystachya* (Piedade et al., 1991). This would not be a suitable species to grow using irrigation in the MENA deserts, as it is an Amazon floodplain grass that is adapted to live in ecosystems where there is abundant water. If it were able to grow in the MENA desert it may sequester 41 – 50 tC ha^{-1}yr^{-1} across 11,430,000km^2, a figure over 5 times higher than the annual non-land-use-change anthropogenic C emissions. This chapter will aim to find a plant species that is capable of sequestering carbon at a high rate for a reasonable rate of water consumption.

2.3 Transpiration

In order to estimate how efficiently a plant uses water when building carbohydrate and hence how efficiently it sequesters carbon, one must consider transpiration. Transpiration is the loss of water vapour, mainly from the leaves of plants. Only about 2% of the water absorbed by a plant is used within the plant with the other 98% lost as water vapour (Forbes and R. Drennan Watson, 1992, p.60).

2.3.1 Transpiration efficiency and ratio

Transpiration efficiency is the ratio of the mass of DM produced to the mass of water transpired and the transpiration ratio is reciprocal (Ehlers and Goss, 2003).

TE = g dry matter (DM) l^{-1} water. TR = litres water transpired kg^{-1} DM produced.

Equation 2.2 Transpiration efficiency and transpiration ratio.

C_4 crops such as Millet, Sorghum and Maize have a greater TE than C_3 plants such as Wheat and Barley (Forbes and R. Drennan Watson, 1992, p.59). However environmental conditions also affect the TE. Tanner and Sinclair (1983, cited in Ehlers and Goss, 2003, p.139) showed that maize grown in a humid greenhouse had a TR of 214 compared with 340 in a dry one. The transpiration rate depends on the potential gradient between the inside and outside of the leaf. High solar radiation, low relative humidity (RH) and high wind all increase transpiration (Forbes and R. Drennan Watson, 1992, p.61), which have implications for plants growing in deserts.

RH in turn is related to air temperature. For a specific humidity level an increase in air temperature will cause a decrease in RH and vice versa. A temperature rise of 5°C – 35°C causes an RH decrease from 100 to 20% (Rao, 2008, p.112). The less water that is present in the air the greater the saturation vapour pressure deficit, the greater the transpiration rate of a plant and the greater the water requirement. This has implications for increased water requirements of plants growing in the MENA deserts, where temperatures are high and relative humidity is low. The Sahara has a RH range of 20—40% (Osborne, 2000, p.20). Below 30% RH is taken as the danger point, below which wildfires are generally more difficult to control (Goldammer, 2004, p.39).

Jyostna Devi et al (2009) studied the TE of seventeen varieties of peanut (*Arachis hypogaea L*) under progressive soil drying regimes. Under well-watered conditions there was little difference in the TE of the varieties averaging 0.00498 (TR 200). Under drought stress the transpiration efficiency ranged from 0.00059 to 0.00253 (TR 1694 to 395). As plants become water stressed they become less efficient at producing biomass per unit of water and hence less effective at sequestering carbon.

Indeed plants risk mortality once soil water reaches the permanent wilting point (usually a pressure of -1.5 MPa in the soil) (Kirkham, 2005, pp.105-106).

2.3.2 Crassulacean acid metabolism plants

C_3 and C_4 plants have already been mentioned, but some plants use an even more water efficient process, known as Crassulacean acid metabolism (CAM), to fix CO_2. These plants can keep their stomata closed during the day and hence limit water loss due to transpiration, fixing stored CO_2 at night (Bartholomew et al., 2003, p.72).

Winter et al. (2005) looked at carbon accumulation and water-use efficiency in tropical conditions of five species of CAM plants and two C_3 plants that can exhibit CAM.

Table 2.1 CAM species

CAM species	Transpiration ratio (g H_2O g-1 dry mass)
Aloe vera	54 ± 6
Ananas comosus	63 ± 10
Euphorbia tirucalli	105 ± 6
Kalanchoe daigremontiana	109 ± 8
Kalanchoe pinnata	106 ± 14
C3 species with CAM metabolism	
Clusia rosea	84 ± 17
Clusia uvitana	227 ± 14

Winter et al., (2005)

Table 2.1 shows that *Aloe Vera* and *Ananas comosus* sequester carbon the most efficiently per amount of water transpired.

2.4 Vegetation to sequester carbon

When considering what species would be suitable to sequester carbon in irrigated MENA deserts, both the speed of growth and transpiration efficiency must be considered as well as other aspects of suitability. We have seen that *Echinochloa Polystachya* can sequester carbon at a tremendous rate, of approximately 40t $ha^{-1}yr^{-1}$. However this species grows in flood plains, in standing water and as such is not water efficient or suited to growing in arid zones.

2.4.1 Ananas comosus (Pineapple)

The pineapple uses the Crassulacean acid metabolism (CAM) process to fix CO_2 and also has a high yield. Bartholomew et al (2003, p.75) cite the transpiration ratio as 50 – 116, but reported the pineapple accumulating 62tDM ha^{-1} over 24 months. This averages 31tDM yr^{-1}, or 13.95tC $ha^{-1}yr^{-1}$ taking agricultural dry matter to be 45% carbon (BFIN, n.d.).

The 11,430,000km^2 of the MENA deserts planted with pineapples could sequester 15.94GtC yr^{-1} for a theoretical H_2O cost of 1771 – 4108km^3 yr^{-1}. However all the water applied to the crop would need to be taken up by the crop which would require a precise irrigation system and no evaporative losses. A serious problem with the pineapple is that it is not a woody plant and the carbon will not be sequestered indefinitely, as its soft tissues will degrade after death. It cannot be harvested like timber for use as a building material, in which the sequestered carbon can remain for many decades or even centuries. The crop could be pyrolysed into biochar (see 3.10) but that would re-release approximately half the carbon as CO_2 (Lehmann et al., 2006).

2.4.2 Bambusa bambos (Bamboo)

Bamboo is a woody grass that can sequester carbon for long periods of time in its dry biomass. It is also a fast growing species. Shanmughavel and Francis (2001) investigated the aboveground biomass production of Bambusa bambos in plantations in Tamil Nadu State. The area had an annual rainfall of 600mm and a mean temperature of 31°C. In 6 years the plantation produced 286t ha^{-1} of above ground DM equivalent to 47.7t DM ha^{-1}yr^{-1}. At 50% carbon (BFIN, n.d.), this equals 23.9tC ha^{-1}yr^{-1}, which is 71% more carbon than is sequestered by the pineapple.

At this rate, 11,430,000km^2 of the MENA deserts planted to *Bambusa bambos* could sequester 27.3GtC yr^{-1}. However in addition to the known amount of rainfall the transplanted seedlings were irrigated for two hours a day and then the plantations were irrigated every fifteen days (Shanmughavel and Francis, 2001). Unfortunately, the authors did not cite the amount of water used to irrigate the bamboo. Scurlock et al (2000) state that bamboo requires a mean annual precipitation of at least 1000 – 1500mm. Komatsu et al (2010) studied transpiration rates of another bamboo: Moso bamboo (*Phyllostachys pubescens*) forests at a stand level and found it to be 567mm a year where the mean annual precipitation was 1790mm. It is unclear what the transpiration rate of *Bambusa bambos* is, although the growth rate is excellent.

2.4.3 Eucalyptus grandis x urophylla

Eucalyptus grandis x *urophylla* is an important tropical timber plantation tree. Stape et al (2004) investigated the Mean Annual Increment (MAI) of stem bark and branches and ANPP of this species in north-eastern Brazil. The authors examined three environmental factors: water, light and nitrogen and their relationship to growth. They found that MAI ranged from 9.4 – 32.6t ha^{-1}yr^{-1} and water was the most limiting factor with an increase of 2.3 t ha^{-1}yr^{-1} for each 100mm yr^{-1} increase in rainfall. The most productive sites use water most efficiently averaging 3.21kg ANPP m^{-3} water transpired (Stape et al., 2004).

Table 2.2 *Eucalyptus grandis* x *urophylla* productivity and C sequestration

Site Nº	Average rainfall	Productivity Class	MAI (stem, bark and branches dry weight)	Coarse roots*	C in stem, bark and branches	C in coarse roots	C in MAI + Coarse roots
	(mm yr^{-1})		(t $ha^{-1}yr^{-1}$)				
1	882	Low	14.9	3.9	7.5	1.9	9.4
2	916	Low	11.1	2.9	5.6	1.4	7.0
3	853	Low	9.4	2.4	4.7	1.2	5.9
4	935	Low	12.5	3.3	6.3	1.6	7.9
5	902	Low	10.9	2.8	5.5	1.4	6.9
6	955	Med	15.1	3.6	7.6	1.8	9.4
7	1143	Med	18.9	4.5	9.5	2.3	11.7
8	958	Med	15.6	3.7	7.8	1.9	9.7
9	1008	Med	15.1	3.6	7.6	1.8	9.4
10	1131	High	16.6	3.0	8.3	1.5	9.8
11	1054	High	18.8	3.4	9.4	1.7	11.1
12	1605	High	19.9	3.6	10.0	1.8	11.7
13	1611	High	31.9	5.7	16.0	2.9	18.8
14	1654	High	32.6	5.9	16.3	2.9	19.2

Low	897	n = 5	12	3.1	6.0	1.6	7.6
Med	1016	n = 4	15.9	3.8	8.0	1.9	9.9
High	1411	n = 5	24	4.3	12.0	2.2	14.2

*Calculated using a below ground to above ground ratio of 26%, 24% and 18% for the low, medium and high classes respectively (Stape et al., 2004). Estimating timber to be 50% DM At 50% carbon (BFIN, n.d.).

Source: Stape et al. (2004); BFIN (n.d.).

Table 2.2 shows that the high sites with an average rainfall of 1411mm yr^{-1} averaged a sequestration rate of 14.2tC $ha^{-1}yr^{-1}$. This is higher than the 13.95tC $ha^{-1}yr^{-1}$ sequestered by pineapple. This species has a greater water requirement than pineapple, but most of the carbon will be sequestered in the form of usable timber (Stape, 2002, p.169).

However, although Table 2.2 shows rainfall it does not show the amount of water actually transpired. Stape et al (2004) also measured this using the Penman-Monteith model.

Table 2.3 Water Use Efficiency

Water Class	Rainfall (mm yr^{-1})	Transpiration (mm yr^{-1})	WUE (kg m^{-3})	MAI + coarse roots (t $ha^{-1}yr^{-1}$)	C in MAI + coarse roots (t $ha^{-1}yr^{-1}$)
Low	886	689	1.59	15.1	7.6
Medium	1055	718	2.24	19.7	9.9
High	1276	869	3.21	28.3	14.2

Source: Stape et al. (2004) revised.

The rainfall differs slightly in the high class between Table 2.2 and Table 2.3, but it can be seen that the high productivity class could sequester 14.2 tC $ha^{-1}yr^{-1}$ (above and below ground). If one ensures that these trees receive enough water to transpire 869mm yr^{-1} and should sequester at least 7.6tC yr^{-1}.

The results presented in Table 2.2 are for plantations of *Eucalyptus grandis* x *urophylla* that were established on soils that had previously hosted grassland or forest, and as such contained more carbon that would be found in a desert soil (Stape et al., 2004) (see Chapter 3). The authors also measured the ANPP, defining it as the difference between MAI and leaf and branch fall. However the amount of carbon returned to the atmosphere from litter breakdown was unknown. Starting from a low level of SOC as in a desert (explored in Chapter 3) the increase in C content of the biomass was a more accurate measure of the net carbon sequestered each year. The amount of carbon that could be sequestered in a forest soil will be explored in Chapter 3.

Figure 2.1 shows the amount of carbon sequestered in the branch, bark, stem and coarse roots of *Eucalyptus grandis x urophylla*.

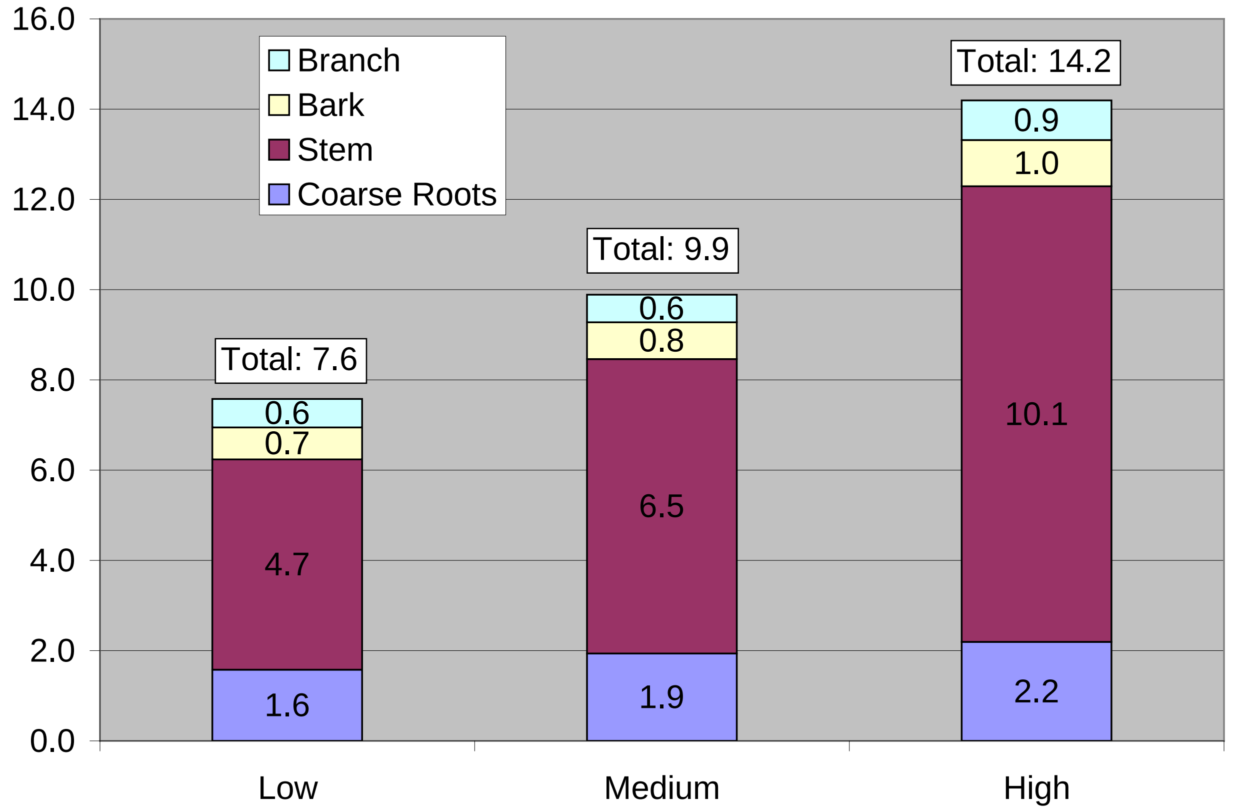

Figure 2.1 Carbon sequestered (t C yr^{-1} ha^{-1}) in low, medium and high productivity stands of *Eucalyptus grandis* x *urophylla* split by component part.

11,430,000km^2 of the MENA deserts planted to clonal *Eucalyptus grandis* x *urophylla* and suitably irrigated could sequester 8.7 – 16.2GtC yr^{-1} in the biomass of the plants. Of this 5.3 – 11.5Gt yr^{-1} (calculated from data in Figure 2.1) will be sequestered in the stem timber of the trees. Calculated using data from Stape (2002). To supply irrigation to match rainfall at the rate of 1276mm yr^{-1} over the area of the MENA deserts would require 14,585km^3. To supply just the transpiration needs of 869mm yr^{-1} would require 9,933km^3.

2.4.3.1 Problems with Eucalyptus grandis x urophylla

Water use of *Eucalyptus grandis* and *Eucalyptus urophylla* have been measured in many studies (Stape et al., 2004; Stape et al., 2004; Stape et al., 2008; Stape et al., 2010; Almeida et al., 2007; Lane et al., 2004). This breadth of available data, together with available data on the growth rate of these trees due to the valuable timber they produce has made *Eucalyptus grandis* x *urophylla* a suitable species for research based on secondary data. This species will be used to model the carbon sequestration potential of vegetation in the MENA deserts in this study.

But are there problems with growing this non-native species in Africa and the Middle East? Ong et al. (2007) researching the water productivity of agroforestry in the semi-arid tropics found that although Eucalyptus is often considered a problem in rural Africa because of its high water demand and the subsequent effects on water supply for irrigation. However, the species has a very high water use efficiency and the transpiration rate per unit leaf area is lower than many other tree species. The proposed planting of *Eucalyptus grandis x urophylla* in this thesis would be on hyperarid desert and would not rely on natural rainfall or groundwater. In fact much of the dislike of

Eucalyptus grandis is due to its evergreen canopy and the inability to farm crops below it (Ong et al., 2007), which would not be an issue in the MENA deserts.

Olievira et al. (2002) developed a model for fire risk and mapped *Eucalyptus sp.* stands in Três Barras, Brazil. Categories included vegetation cover, fuel load and wind. The Eucalyptus stands were classified as high risk, whereas pine plantations were classified as very high and extreme risk. Swamp and areas available for plantation were at moderate risk. So overall *Eucalyptus sp.* plantations did not pose as great a risk as pine. Fuel loading, the litter on a forest floor, is one of the major factors in determining how a fire will behave. Above 60t ha^{-1} is classified as extreme risk, while below 19t ha^{-1} is low risk. Hot dry winds are more of a fire risk than humid winds Olievira et al. (2002). Therefore an irrigated forest in the MENA region must contain firebreaks (explored in section 6.2.1) and consideration must be given to clearing away build up of ground vegetation to reduce fire load. In a young forest established in desert by irrigation and with removal of ground litter the fuel load should remain below that classified as low risk.

Eucalyptus sp. plantations in particular have been criticised by environmentalists, such as Wangari Maathai (Okella, 2009) who cites problems such lack of biodiversity and overuse of ground water. It is true that a monoculture does not support the biodiversity of a mixed species ecosystem, is less resilient to environmental change and more prone to degradation of both the above and belowground biota (Wittebolle et al., 2009). However, two things must be stressed that for the purposes of this thesis.

1. *Eucalyptus grandis* x *urophylla* has being chosen as a proof of concept model due to the known carbon sequestration potential and water use efficiency. A multi-layered forest ecosystem would bring in too many variables to model in this thesis. Furthermore there was insufficient data available on the carbon sequestration potential and transpiration efficiency of indigenous trees.
2. Even if *Eucalyptus grandis* x *urophylla* were grown as a monoculture in the MENA deserts, it would be on land which is currently hyperarid desert, with solar-desalinated irrigation used to supply all the water that the forest requires. Any oases or areas where biodiverse hotspots may be present in the Sahara or Arabian deserts would be avoided, with the land free of irrigation and unplanted.

2.5 Nutrient requirement

As well as CO_2 and water, plants require nutrients for growth. Lal estimates that to sequester 1GtC in the world soils, 80million t of nitrogen, 20million t of Phosphorus, and 15million t of potassium would be required, but suggests that biological nitrogen fixation; subsoil recycling and aerial deposition could provide many of these requirements (2004a). Ornstein et al (2009) states ‘there are no desert-wide, mineral deficiencies of potassium, phosphate and trace elements, differentiating deserts from other regions which support lush growth’ such as the Congo or Amazon basin, which would limit the establishment of a forest on land that has been previously desert’. This will require further research to verify.

2.6 Succession and restoration.

Ecosystems change in terms of *in situ* vegetation over time in a process called succession, often leading to a more stable state (Osborne, 2000, p.233). Primary succession occurs when an environment that has never supported life such as a newly exposed bare rock or a volcanic island are colonised by pioneer species, often lichens then mosses. During primary succession plant species can are in constant competition with each other resulting in the loss of some species when the rhizosphere conditions are unfavourable. There is a shift from small, short-lived, rapidly-reproducing plants which produce high quality nutritious litter as the dominant species to larger, longer-lived, plants which are slower to reproduce and that conserve more of the nutrients that they absorb within their body tissue (Walker et al., 2007, p.46) and they establish mutual associations with soil fungi (Smith and Read, 2008).

Secondary succession occurs when land that has previous supported natural ecosystems is allowed to revert to nature, such as when farmland is abandoned (Osborne, 2000, p.233). Environmental restoration can mimic the process of succession, aiming to manipulate succession to accelerate ecosystem changes to the desired state. The biggest difference between succession and restoration is timescale, with restoration taking years rather than centuries (Walker et al., 2007, p.4). The ecosystem and the succession to that ecosystem are consciously designed.

Eucalyptus grandis x urophylla is a tropical forest tree. The transformation from a MENA desert to a forest may need to pass through succession stages using drought tolerant species to assist in stabilising the sand, improving water retention, adding nitrogen, capturing dust and lowering water vapour deficits, before species that are faster at sequestering carbon are introduced to the system. A variety of techniques can be used to stabilise sand dunes.

Li et al (2006) showed that the straw checkerboards increase the entrapment of dust deposition in dunes and that enhances topsoil development by increasing the accumulation of silt and clay contents, improves the soil habitat for plant invasion and establishment, and increases soil nutrient and water-holding capacity.

Figure 2.2 Straw inserted vertically into sand dunes in a checkerboard-pattern sand barrier.

Source: Zheng and Huang, (2009)

The collection of dust in desert landscapes can have positive effects on soil building and restoration. Drees et al (1993) investigated the characteristics of aeolian dusts in Niger after the Harmattan wind season, which blows dust from the Sahara. They found that 2tonnes $ha^{-1}yr^{-1}$ of dust was deposited bringing water soluble Ca, K, Mg and Na.

The deep, extensive root system of certain trees can capture nutrients and bring them to the surface. Leguminous nitrogen-fixing trees, such as *Faidherbia albida* and *Acacia senegal* are especially useful in agroforestry situations. Once established these pioneer trees reduce nutrient losses from wind erosion and capture silt and clay particles from the air increasing the soil's clay content (FAO, 2004, p.23). The leaf litter of woody plants is rich in polyphenols that assists in build up of SOC (Abril and Bucher, 2001). Tree species suitable for afforestation in dryland ecosystems include *Mesquite, Acacia* and *Neem* (Lal, 2003).

Table 2.4 summarises pioneer trees that require 150-500mm rainfall yr^{-1} that could be used in the early stages of environmental restoration.

Table 2.4 Drought tolerant African trees and shrubs used in agroforestry that live in an environment with 150 – 500mm annual rainfall.

Scientific Name	Common name	Suitable for: (soils)
Acacia mellifera	(Black thorn)	Shallow, alkaline, heavy or light soils with a low water table
Acacia saligna	(Orange wattle)	Shallow, saline, infertile, alkaline soils with a low water table
Acacia Senegal	(Gum arabic)	Shallow, acid or alkaline, light soils
Acacia seyal	(Shittim wood)	Shallow, infertile, alkaline, heavy or light soils
Acacia tortilis	(Umbrella thorn)	Shallow, saline, infertile, alkaline, light soils with a low water table
Anacardium occidentalis	(Cashew nut)	Infertile, light soils
Annona senegalensis	(Wild soursop)	Shallow, infertile, light soils
Boscia senegalensis	(Senegal boscia)	Infertile, heavy or light soils
Commiphora africana	(African myrrh)	Alkaline, heavy or light soils
Croton macrostachys	(Broad-leaved croton)	Light soils
Faidherbia albida	(Ana tree)	Light, saline soils
Ficus sycomorus	(Wild fig)	Light soils
Jatropha curcas	(Chinese castor oil)	Shallow, infertile soils

Scientific Name	Common name	Suitable for: (soils)
Moringa oleifera	(Drumstick tree)	Shallow, acid, heavy or light soils
Phoenix chilensis	(Mesquite/Algarrobo)	Shallow, saline infertile, alkaline, light soils
Senna siamea	(Black-wood cassia)	Acid or alkaline, light soils with a low water table
Senna spectabilis	(Yellow shower)	Light soils
Tamarix aphylla	(Leafless tamarisk)	Saline, infertile, alkaline, heavy or light soils

Source: Agroforestry in Africa (n.d.) in Hove (2010)

Table D1 in Appendix D is a much-extended version of this table that shows tree species that require more water and that could be used in a succession as the desert proceeds towards forest.

2.7 Irrigation

In 2008 there were 306,247,000ha of land equipped for irrigation (FAO, 2010). This is an area larger than the entire Arabian Desert. Water that falls as rain, or is applied as overhead irrigation, is subject to evaporation, both from the soil surface and the surface of the plants leaves. Transpiration combined with evaporation makes up evapotranspiration. The amount of evapotranspiration can be calculated by the FAO Penman-Monteith equation, which requires inputs of mean temperature, wind speed, relative humidity, and solar radiation (Allen et al., 1998). Reducing evaporation particularly in irrigated plantations is easier to achieve than reducing transpiration.

2.7.1 Drip irrigation

Well-organized irrigation can be twice as efficient as precipitation in getting water to trees (Howell, 2001). Forbes and Watson (1992), report that few regions receive enough rainfall to balance evapotranspiration all year and irrigation is needed to achieve good yields.. Drip irrigation where water is dripped from the nozzle of a hose onto individual plants only wets the soil around the root zone, which can be just 30% of the volume of soil wetted by the other irrigation methods. There are also reductions in deep percolation, surface runoff and in evaporation from the soil (Brouwer et al., 1988).

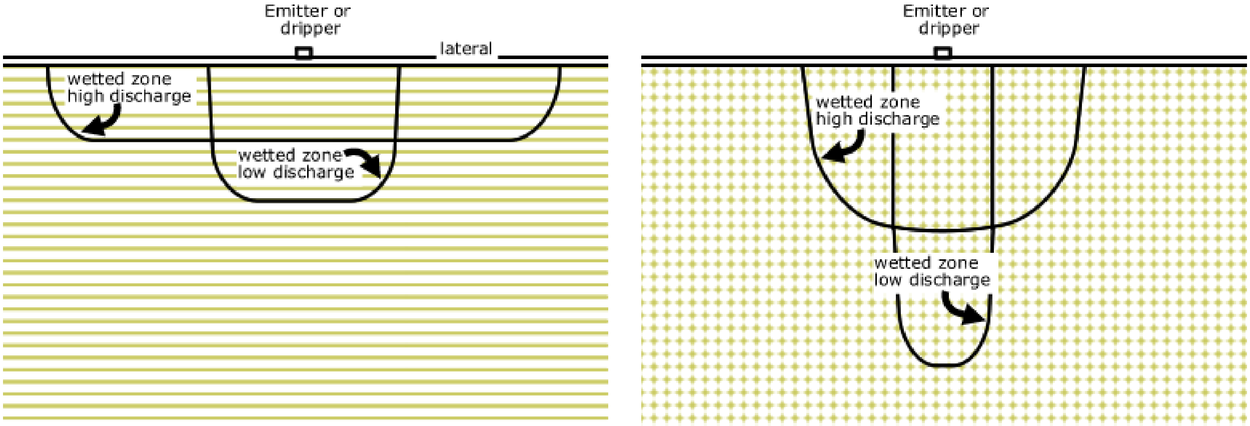

Figure 2.3 Drip irrigation patterns in clay (left) and sand (right) with high and low discharge rates.

Source: Source: User created redrawn from Brouwer et al. (1988)

Figure 2.3 illustrates the drip irrigation pattern in clay and sand at high and low discharge rates. A discharge rate that is too high in sand will result in water being lost in the soil profile. This highlights the importance of matching irrigation rate to transpiration requirement in the MENA deserts.

2.7.2 Micro-irrigation

Zimbabean experiments show that over half the water applied to the surface of irrigated gardens can be lost as soil evaporation. These losses can be minimised by using micro-irrigation techniques that reduce soil evaporation, drainage losses and canopy interception. Clay pipes or bamboo can be used for cheap, simple subsurface irrigation to improve yields, quality and water use efficiency (Batchelor et al., 1996). Buried clay pot irrigation is an efficient method of irrigation where unglazed porous clay pots are buried to their rim next to vegetables or orchard trees. They are filled with water that seeps through the pots and waters the plants. Clay pots have been used to establish dry orchards in India and in Pakistan seedling establishment rates have been reported at 96.5% compared to 62% for hand watering (Bainbridge, 2001). Eucalyptus and Acacia has been established in areas of Pakistan with 200mm annual rainfall using this technique (Bainbridge, 2007, p.252).

2.7.2.1 Deep pipe irrigation

Another technique is deep pipe irrigation. This involves using an open vertical pipe to deliver irrigation water directly to tree roots. Combined with the use of tree-shelters one or two litres per seedling per month can be sufficient for seedling establishment. A 50mm diameter bamboo with internodes removed with a series of holes drilled on the tree-side is placed next to the seedling. (Bainbridge, 2007, pp.246-247).

A plant growing where an adequate water supply is continuously available will develop a shallow and less extensive root system than the same species in a drier soil (Forbes and R. Drennan Watson, 1992). Deep pipe irrigation can be combined with drip irrigation to gain the benefits of drip irrigation while ensuring the tree develops a good root system.

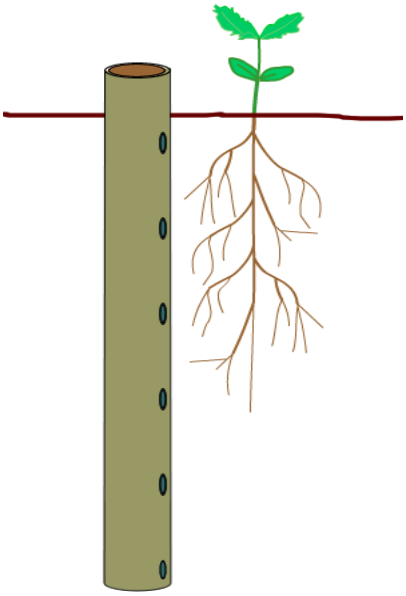

Figure 2.4 Deep Pipe Irrigation

Source: User created draw from description in Bainbridge (2007, pp.246-247).

2.7.3 CO_2 release due to irrigation

Traditional irrigation of semiarid lands from groundwater can release CO_2 in two ways. It may be pumped using fossil fuels as an energy source. Less obviously groundwater used for irrigation often contains CO_2 at a much higher partial pressure than in the atmosphere. Reaching equilibrium at the surface can cause release of this CO_2 to the atmosphere. Often these groundwaters also contain high concentrations of dissolved calcium that can precipitate into the soil forming calcium carbonate and releasing CO_2. For example, an annual application of 1m of irrigation water at 40mg Ca l^{-1} would degas 12 gC $m^{-2}yr^{-1}$ as CO_2 as the carbonate precipitates. (Schlesinger, 2000).

$$Ca^{2+} + 2HCO_3^{-} \rightarrow CaCO_3 \downarrow + H_2O + CO_2 \uparrow$$

Equation 2.3 CO_2 degassing as carbonate precipitates

Conversely, carbonates can leach into the groundwater if soils are irrigated with water containing low levels of carbonates (Lal, 2004a). Irrigating land with solar-desalinated seawater should not cause the release of CO_2, as long as renewable energy is used to pump the water as well as desalinate it.

2.8 Summary

Chapter 2 investigated various plants species with a view to estimating how much carbon could be sequestered annually in the Sahara and Arabian deserts. It found that if irrigated the MENA deserts have the potential to grow vegetation that can sequester large amounts of atmospheric carbon. If the whole area of the MENA deserts could be irrigated *Ananas comosus*, *Bambusa bambos* and *Eucalyptus grandis x urophylla* could sequester a maximum of 15.94, 27.3 and 18.5 GtC yr^{-1} respectively, all of which exceed the 8.7GtC of non-land-use-change anthropomorphic emissions of 2008.

Water requirements have been more difficult to ascertain. *Ananas comosus* had the highest transpiration efficiency of the species investigated theoretically transpiring 2024 – 4697m^3 water ha^{-1}yr^{-1}. The transpiration efficiency of *Bambusa bambos* is unknown, (but based on other bamboo species highly unlikely to be less than either *Ananas comosus* or *Eucalyptus grandis x urophylla*) which is unfortunate given the species' growth rate. *Eucalyptus grandis x urophylla* is a well-documented forestry tree. At the highest growth rate it transpires 8,690m^3 water ha^{-1}yr^{-1}. The exact water requirement is unknown. Although Howell (2001) states irrigation can be twice as efficient as rainfall, the amount of irrigation cannot fall below the actual value of water required to be transpired by the vegetation.

This chapter looked at the ecological restoration that might make the environment more suitable for growing tropical forest trees and examined highly efficient forms of irrigation including drip mechanisms in combination with deep pipe irrigation. More research is needed on all these subjects. The question in this thesis cannot be answered using *Bambusa bambos* because its water requirements are unknown. *Ananas comosus* has very low water requirements, but does not sequester carbon in a form that can be readily stored. Biochar is possibility, but this would be research for another thesis. Due to reasonably known water requirements and the ability to store for long periods of time as timber *Eucalyptus grandis x urophylla* is a good candidate species to use to sequester carbon in the MENA deserts.

The exact water requirement of *Eucalyptus grandis x urophylla* using precisely applied drip-irrigation in combination with deep pipes is unknown. A range of 9,000 – 10,000m^{3}ha^{-1} of will be chosen to work with. Both figures are higher than the transpiration rate for all three classes (Table 2.3). If this irrigation matches or exceeds transpiration rate of the trees, the species could sequester 8.7 – 16.2 GtC yr^{-1} over 11,430,000km^3 of MENA deserts for a water requirement of 10,287 to 11,430km^3. As the figure of 9,000 – 10,000m^{3}ha^{-1} is an estimation, further work will be needed to verify it.

2.8.1 Key Data from Chapter 2

C sequestration potential of *E. grandis* x *urophylla*:	**8.7 – 16.2 GtC yr^{-1}.**
Calculated from source data in: Stape et al. (2004)	
Water requirements of *E. grandis* x *urophylla*:	**10,287 – 11,430 km^3 yr^{-1}.**
Calculated from source data in: Stape et al. (2004)	

Box 2.2 Key data from Chapter 2

Chapter 3 Soil Carbon

3.1 Introduction

This chapter will investigate the carbon storage capacity of soil. The soil carbon of various ecosystems will be considered along with respiration rates and SIC. The soil types of the MENA region and current SOC and SIC content will be described in order to better understand their potential to store additional carbon under irrigated conditions. The importance of mycorrhiza will be discussed and biochar will be mentioned briefly.

Soil is an important store of carbon. Estimates vary with the standard figure in the literature stating that global soils contain 1500GtC (Luo and Zhou, 2006, p.57). However, Sabine et al. (2004) suggest a figure of 3150Gt if the carbon in frozen soils and deeper layers is included. These estimates are much higher than the current atmospheric carbon of 826.8Gt (ESRL, 2010).

3.2 Soil carbon of various ecosystems

Ecosystems vary in the amount of carbon they contain in soil and vegetation.

Table 3.1 Soil carbon stocks in vegetation and soil carbon pools down to a depth of 1 metre

		Carbon stock (Gt)			Carbon t ha^{-1}		
Biome	Area (10^9 ha)	Veg$^{n.}$	Soil	Total	Veg$^{n.}$	Soil	Total
Tropical forests	1.76	212	216	428	120.5	122.7	243.2
Temperate forests	1.04	59	100	159	56.7	96.2	152.9
Boreal forests	1.37	88	471	559	64.2	343.8	408.0
Tropical savannas	2.25	66	264	330	29.3	117.3	146.7
Temperate grasslands	1.25	9	295	304	7.2	236.0	243.2
Deserts and semi-deserts	4.55	8	191	199	1.8	42.0	43.7
Tundra	0.95	6	121	127	6.3	127.4	133.7
Wetlands	0.35	15	225	240	42.9	642.9	685.7
Croplands	1.6	3	128	131	1.9	80.0	81.9
Total	15.12	466	2011	2477	30.8	133.0	163.8

Watson et al. (2000, p.4)

Table 3.1 shows that tropical forests hold a higher proportion of their carbon in vegetation than other forest types. Soils contain nearly as much carbon as the vegetation under rainforest, but considerably exceed the biomass in all other ecosystems; in the case of grassland the soils hold 33 times the carbon as the vegetation.

3.3 Soil Respiration

Atmospheric carbon becomes SOM via the process of photosynthesis that occurs in green plants. Soil respiration plays an important role in the carbon cycle. Root and rhizosphere respiration, decomposition of litter and the oxidation of SOM all produce CO_2 in soil (Luo and Zhou, 2006, pp.17-22). This reduces the net flow of carbon from the atmosphere into an ecosystem as a whole. To put this in context the whole of the CO_2 flow must be considered and the role of autotrophs and heterotrophs.

Table 3.2 Properties of autotrophs and heterotrophs

	Autotrophs		Heterotrophs	
	Photoautotroph	Chemoautotroph	Photoheterotroph	Chemoheterotroph
Energy Source	Light	Inorganic oxidation	Light	Inorganic oxidation
Carbon Source	CO2	CO_2	Organic carbon	Organic carbon
Examples	All green plants	Nitrifying bacteria	Some purple and green bacteria	Most bacteria, fungi, animals

Source: Grant et al. (2005, p.4)

Photosynthesis by photoautotrophs such as trees incorporates carbon into plant tissues. In a terrestrial ecosystem, such as a forest, this carbon comes from atmospheric CO_2. The rate at which these primary producers produce biomass e.g. t $ha^{-1}yr^{-1}$ defines an ecosystem's gross primary production (GPP). Photoautotrophs, like all living organisms, respire, causing some of the carbon incorporated in their tissues to be released back into the environment as CO_2. Subtracting this carbon (plant respiration - R_p) from that assimilated during photosynthesis gives an ecosystem's net primary production (NPP) (Luo and Zhou, 2006, pp.18-19).

Although the NPP takes into account that portion of soil respiration that is attributed to the primary producers it does not take into account microbial respiration. Live and dead microorganisms mix with dead material from plants, such as leaf litter and dead roots to form SOM. SOM can last for thousands of years, until soil microbes eventually break it down during microbial respiration (R_m). Subtracting microbial respiration from the NPP gives the net ecosystem production (NEP), which is a more accurate representation of the net transfer of carbon from atmosphere. This value can be negative if ecosystem respiration exceeds photosynthesis (Luo and Zhou, 2006, pp.18-19).

Looking at the respiration another way, respiration by primary producers can be from the above ground parts of the plants (R_a) or from the below ground part of the plants (R_b). R_b added to microbial respiration (R_m) gives the soil respiration (R_s). The R_a added to the R_s gives the total ecosystem respiration (R_e). Subtracting R_e from the GPP gives the NEP (Luo and Zhou, 2006, pp.18-19).

Table 3.3 Respiration summary

Plant respiration = aboveground plant respiration + belowground plant respiration	$R_p = R_a + R_b$
Net primary production = gross primary production – plant respiration	$NPP = GPP - R_p$
Soil respiration = belowground plant respiration + microbial respiration	$R_s = R_b + R_m$
Ecosystem respiration = aboveground plant respiration + soil respiration	$R_e = R_a + R_s$
Net ecosystem production = gross primary production – ecosystem respiration Net ecosystem production = gross primary production – aboveground plant respiration – soil respiration	$NEP = GPP - R_e$ $NEP = GPP – R_a - R_s$
Net ecosystem production = net primary production – microbial respiration Net ecosystem production = net primary production + belowground plant respiration – soil respiration	$NEP = NPP - R_m$ $NEP = NPP + R_b - R_s$

Source: Luo and Zhou (2006, pp.18-19)

The CO_2 transport systems in an ecosystem are illustrated in Figure 3.1.

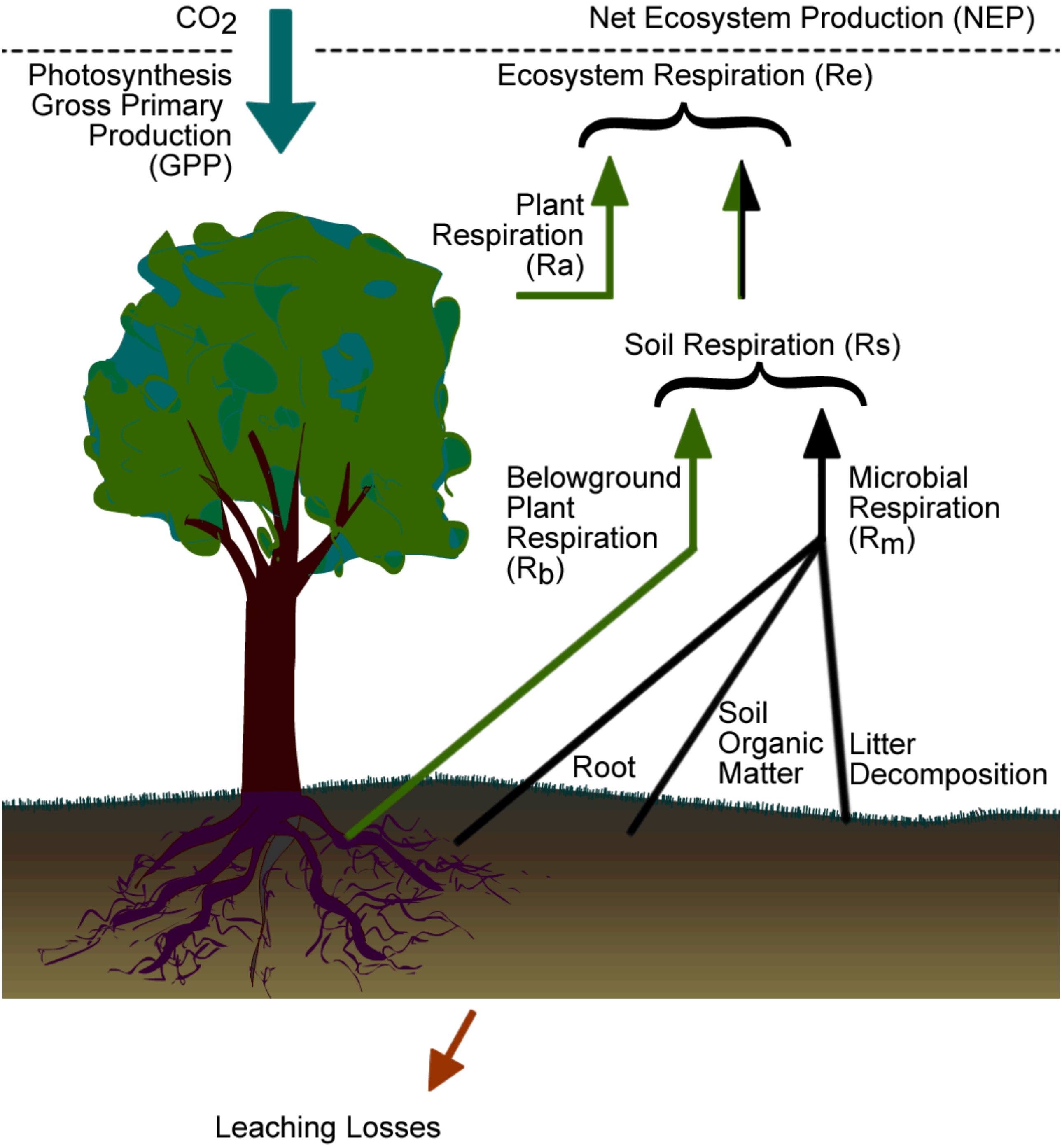

Figure 3.1 CO_2 transport in an ecosystem

Source: Redrawn from Luo and Zhou (2006, p.18)

An increase in NPP due to higher temperatures does not ensure an increase in NEP. It can decrease and even become negative because of the rate of increase in SOM decomposition (Zheng et al., 2009). So when considering the carbon budget of established ecosystems and especially their potential to sequester carbon it is vital to include the CO_2 effluxes from the soil. Consider the data in Table 3.4.

Table 3.4 Annual carbon fluxes for mid-rotation loblolly pine plantations (tC $ha^{-1}yr^{-1}$)

Component	Control	Irrigated	Fertilised	Fertilised and irrigated
Soil CO_2 evolution (R_s)	12.63	14.89	12.93	15.76
Root respiration (R_b)	6.63	7.45	9.42	10.62
Microbial respiration (R_m)	6	7.44	3.51	5.14
Net primary production (NPP)	5	6.35	10.20	12.35
Net ecosystem production (NEP) (NPP – R_m)	-1	-1.09	6.69	7.21

Source: Maier and Kress (2000)

Relying only on NPP data, the forests in all the treatments appear to be sequestering atmospheric carbon. However, once microbial respiration is taken into account it can be seen that the control and the irrigated plantation are net emitters of carbon. This study was from a mid rotation plantation (age 11 years) in North Carolina planted on land that had previously also been forestry plantation (Maier and Kress, 2000).

3.3.1 Belowground carbon allocation and release

Plants allocate C belowground to produce roots, enable them to respire, and support mycorrhizae. Total belowground carbon allocation (TBCA) can exceed 30% of GPP and all aboveground NPP (Giardina and Ryan, 2002). Giardina and Ryan (2002) measured total belowground carbon allocation (TBCA) in a fast-growing *Eucalyptus saligna* in Brazil. They found that 97% of TBCA was quickly returned to the atmosphere through soil respiration.

Högberg and Read (2006) determined that half of total soil carbon release is from living plant roots, their mycorrhizal fungi and other root-associated microbes, and that this release is driven directly by recent photosynthesis.

3.4 Soil respiration rates of various ecosystems

Soils in different biomes respire at different rates. The Loblolly pine ecosystem is an example of a temperate forest biome. Wei et al (2010) found soil respiration to average at 5.21, 9.00 and 14.89 tC $ha^{-1}yr^{-1}$ for boreal, temperate and tropical forests respectively. These figures refer to soil respiration rates they include both belowground plant respiration and soil microbial respiration.

Rastogi et al. (2002) have estimated the total CO_2 efflux for a variety of biomes.

Table 3.5. Efflux of CO_2 (million t C yr^{-1}) from different biomes

Biome	Below ground mortmass decomposition	Litter decomposi -tion	SOM decomposi -tion	Root respiration	% Root respiration
Polar desert	0.2	0.2	0.1	0.2	40%
Tundra	194.4	119.8	18.1	108.6	33%
Forest tundra/ sparse taiga	248.2	340	17.0	210.8	35%
Taiga	476	996	42.0	672.7	44%
Mixed-deciduous forest	168	246.4	11.2	243.0	57%
Forest-steppe	341	233.2	11.0	221.7	38%
Steppe	549	182.5	9.4	232.1	31%
Subtropical woodland	2.6	2.2	0.1	2.3	47%
Desert–semi desert	487	182.7	5.2	215.8	32%
Total	2467	2273.1	114.0	1907.1	39%

Source: Rastogi et al. (2002)

Table 3.5 shows that the percentage root respiration of below ground respiration ranged from 23% in the case of desert/semi-desert to 57% in mixed deciduous woodland. Hanson et al (2000) correlated studies investigating the contribution of root respiration to total soil respiration. The studies, which covered a full growing season, showed that the root respiration contributes 45.8% and 60.4% of below ground respiration in forest and non-forest vegetation, respectively. These figures differ slightly from those presented in Table 3.5.

Jia et al. (2006) reported a figure of 36.8% for Leymus chinensis in the Mongolian Steppe, which is closer to Rastogi's figure for Steppe (31%) than Hanson's figure for general non-forest vegetation (60.4%). This shows that variations exist even within the same biome. This may be due to differences in experimental technique or environmental conditions such as temperature. This efflux is from established biomes. The efflux during the transformation from desert to forest would need to be measured *in situ*.

Root respiration is a necessary part of biomass accumulation in photoautotrophic organisms. Microbial respiration decreases soil carbon levels.

3.5 Soil Inorganic Carbon

In addition to SOC, consideration must be given to the quantity of soil inorganic carbon (SIC). This is particularly true of dryland soils that contain at least as much as or more SIC than SOC (Lal, 2003). SIC can be lithogenic inorganic C which is inherited from parent material of the soil or pedogenic inorganic C which is formed through the dissolution and precipitation of carbonate parent material (Wu et al., 2009).

Lal (2003) suggests that there is potential of SIC sequestration in dryland soils through the formation of secondary carbonates. This can occur if Ca^{+2} and Mg^{+2} cations are supplied from outside the ecosystem in dust, rainwater or fertilizer. The CO_2 in the soil forms carbonic acid that can precipitate as carbonates of calcium or magnesium.

The process is as follows:

$$CO_2 + H_2O \rightleftarrows H^+ + H\,HCO_3^- \rightleftarrows H_2CO_3$$

$$Ca^{+2} + 2\,HCO_3^- \rightleftarrows Ca\,HCO_3^- + H_2CO_3$$

$$Ca^{+2} + HCO_3^- \rightleftarrows CaCO_3 + H$$

Equation 3.1 Carbonic acid formation

Source: Lal (2003)

There are synergies between SOC and secondary carbonates. Carbonates increase with SOC applications due to the microbial activity causing an increase in soil CO_2 through respiration (Lal, 2003). Therefore increasing SOC can also increase SIC.

3.6 Soil types of the MENA region

The Sahara, and the deserts of the Arabian Peninsula represent the zone of tropical deserts. These have high mean annual temperatures and precipitation far below 100mm. Most of the deserts have extra-arid climates. Arid, semi-arid and dry sub-humid areas are marginal zones around the deserts. Soil carbon in the extra-arid deserts is 2 – 5t ha^{-1} with biomass adding a negligible 0.1t ha^{-1} (Lioubimtseva et al., 1998).

Lal has listed the SOC and SIC content of soils based on the USDA classification system. Deckers et al have translated this into the FAO classification system. Soil types of the MENA region and their carbon content are given in Table 3.6.

Table 3.6 Soil types and carbon content of soils that predominate in the MENA deserts

Soil order USDA classification	Soil order FAO classification match.	SOC Density (t ha^{-1})	SIC Density (t ha^{-1})
Aridisols	Solonchaks, Solonetz, Gypsisols, Durisols, Calcisols, Arenosols	38	290
Entisols	Regosols	42	124
Rocky land		17	0
Shifting sand		4	9

Source: Lal (2004b); Deckers et al. (2002). See Appendix E for an extended table.

The entisols and aridisols that make up most of the land of the MENA deserts contain little SOC and more SIC. The shifting sands and rocky land contains negligible amounts of carbon. Figure 3.2 shows the soil orders of the MENA region based on the USDA classification system.

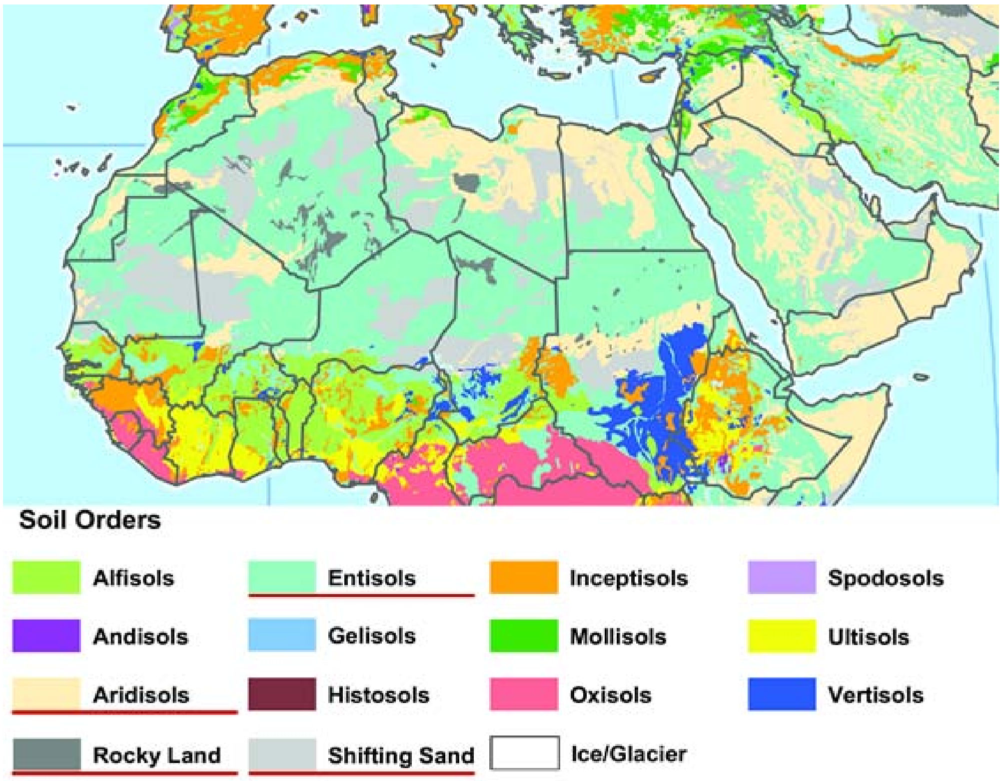

Figure 3.2 Soil type map of the MENA region based on the USDA classification system with desert soils underlined in red in the key.

Source: USDA (2005) Modified.

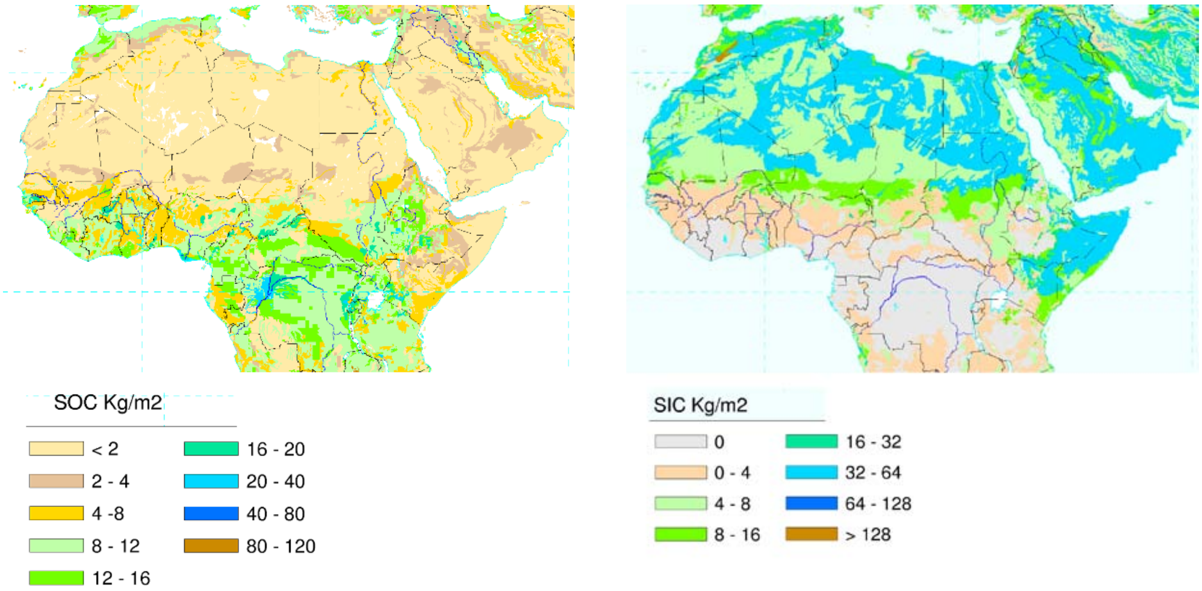

Figure 3.3 SOC and SIC of MENA soils

Source: USDA (2000b); USDA (2000a) modified

Figure 3.3 shows the SOC and SIC content of the soils of the MENA region. The soils contain little organic carbon and more inorganic carbon.

3.7 Soil Damage

Global soils are damaged and present agricultural and forestry practices are compounding the damage (Lal, 2004b). Furthermore, soil respiration and the consequential efflux of CO_2 increases with increasing temperature (Zheng et al., 2009; Wei et al., 2010), so in the context of global warming soil CO_2 efflux is part of a positive feedback loop (Cox et al., 2000). SOC can be labile, composed of unstable carbohydrates and proteins or recalcitrant, which are more stable; mostly lignin (Rovira and Vallejo, 2002). Labile soil carbon is more temperature sensitive than old, recalcitrant SOM (Luo et al., 2001).

Poor agronomic practices leads to cultivated soils often washed into rivers and then the oceans by erosion. There, out-gassing of CO_2 can occur (Richey et al., 2002). Between 1850 and 1998 terrestrial ecosystems lost 136 ± 55GtC including 78 ± 12GtC from soil. Of the soil losses one-third is due to degradation and erosion, and the rest is due to mineralisation (Lal, 2004a). During the 1990s land use change released 1.4–3.0GtC yr^{-1} (Houghton, 2002). This figure is 16%-34% of the 8.7GtC emitted through non-land-use-change anthropogenic activities in 2008 (Le Quéré et al., 2009).

Table 3.7 summarises C loss due to cultivation in soils under various biomes and of various types.

Table 3.7 Mass of carbon present in different soils and its loss due to cultivation

Soil type	Area (million km^2)	Organic C content (t ha^{-1})	Mass of C in virgin soil (Gt)	Mass of C in cultivated soil (Gt)	Loss of C due to cultivation (Gt)
Temperate forest soil	3.08	69–142	24.4	18.1	6.3
Temperate grassland soil	3.25	125–184	49.8	36.9	12.9
Tropical forest soil	4.39	71–145	47.3	35.1	12.2
Tropical grassland	1.61	94–178	21.4	15.9	5.5
Saline sodic arid soil	3.08	26–71	17.7	13.1	4.6
Wetlands/Paddy soil	0.89	119	10.6	7.8	2.8
Histosol	0.39	1120	43.6	35.6	8.0
Andosol	0.31	237	7.3	5.4	1.9
Total	17.27	-	222	168	54

Source: Rastogi et al. (2002)

Guo and Gifford (2002) performed a meta-analysis of 80 reports detailing conversion of grassland to cropland and found it always led to soil carbon loss. This loss averaged 59%, and was highest (78%) with low annual rainfall (400–500mm)

A major cause of soil and ecosystem damage is burning. The burring of tropical grasslands emits 2.4–4.2GtC yr^{-1}, which is greater than the 1.8GtC yr^{-1} emitted from deforestation. Frequent burning means grasslands may not recuperate (Neely et al., 2009).

3.8 Soil Repair

If this trend of soil damage could be reversed, ecosystem repair could sequester large amounts of amounts of atmospheric CO_2 as SOM and help mitigate climate change (Lal, 2004a). When agricultural land is allowed to revert to natural vegetation or replanted to perennial vegetation, SOC can accumulate (Post and Kwon, 2000). Smith et al. (2008) estimate the mitigation potential from agriculture by 2030, considering all GHGs, is estimated to be approximately 1.5 – 1.6GtCO_2e yr^{-1}.

Lal (2004a) estimates that the potential of carbon sequestration in soils ranges from 0.4 – 1.2GtC yr^{-1} through the adoption of recommended management practices on degraded soils. Sequestration rates range from 0.1t ha^{-1}yr^{-1} in warm dry regions to 1.5

tonnes $ha^{-1}yr^{-1}$ in cool and temperate regions and that the cumulative potential of soil C sequestration over 25–50 years is 30–60Gt (Lal, 2004b).

Table 3.8 Detailed soil sequestration potential of various soil types

Cropland Soils	Range Lands and Grass Lands	Restoration of Degraded and Desertified Soils	Irrigated Soils
13.5millionkm^2 [0.4 - 0.8 GtC yr^{-1}]	[0.01 to 0.3 GtC yr^{-1} ?]* 0.37millionkm^2 in semi-arid and sub-humid regions	0.011millionkm^2 [0.2 - 0.4 GtC yr^{-1}]	2.75millionkm^2 [0.01 - 0.03 GtC yr^{-1}]*
Conservation tillage (0.1-1) Cover crops (0.05-0.25) Manuring and integrated nutrient management (0.05-0.15) Diverse cropping systems (0.05-0.25) Mixed farming (0.05-0.2) Agroforestry (0.1-0.2) Acid savannah soils, 2.5 million km^2 in South America, have a high potential	Grazing management (0.05-0.15) Improved species (0.05-0.1) Fire management (0.05-0.1) Nutrient management *Both SOC and SIC are sequestered	Erosion control by water (0.1-0.2) Erosion control by wind (0.05-0.1) Afforestation on marginal lands (0.05-0.3) Water conservation/ harvesting (0.1-0.2)	Using drip/sub-irrigation Providing drainage (0.1-0.2) Controlling salinity (0.06-0.2) Enhancing water use efficiency / water conservation (0.1-0.2) *Both SOC and SIC are sequestered

Source: Lal (2004a)

3.8.1 Soil organic carbon under secondary forest succession

SOC content of the top 20cm of soil was measured during the secondary forest succession in north Ziwulin region in the middle of Loess Plateau, China. The SOC increased from 0.72% after 1 year to 1.72% after nine years peaking at 2.22% after seventeen years (Jia et al., 2005). In eight years the SOC increased by 1% in the top 20cm. For the 8 years between years one and nine this equalled 2.9t yr^{-1} ha^{-1} in the top 20 cm. This increase may have extended down the soil profile further, but this was not researched. Averaged over the first 16 years the rate of sequestration was 1.9t yr^{-1} ha^{-1} in the top 20cm.

3.8.2 Soil organic carbon under repaired grasslands

Cropland, rangeland, desertified lands, and irrigated soils offer the greatest potential for carbon sequestration (Lal, 2004a). Potter et al. (1999) compared the amount of SOC of previously cultivated clay soils (Udic Haplusterts) in Texas restored to perennial grassland 6, 26 and 60 years earlier, to soils under continuous cultivation for a century and to virgin prairie soil. There was 4.4 – 6% SOC in the surface 5cm of the prairie soil compared to 1.5 – 1.9% in the agricultural sites, with the SOC in the grasslands an intermediate value. There was 25 - 43% less SOC in the top 1.2m of the agricultural soil compared to the prairie. The restored grasslands sequestered carbon in the surface 60cm at a linear rate of 0.447tC $ha^{-1}yr^{-1}$ suggesting it will take another century for the 60-year-old grassland soil to attain the SOC of the prairie.

Research at the Fermilab chronosequence shows that restoring prairie vegetation can rebuild shallow SOC at rates of 0.33 - 1.5tC $ha^{-1}yr^{-1}$, depending on soil type. Carbon inputs are mainly root and rhizome production. Within 12 years the aboveground plant mass reaches levels of a remnant prairie, but the root system recovery takes about 52 years (CSiTE 2006, pp.A-5). This increases in SOC in the prairie described by Potter et al (1999) of 0.447t ha^{-1} yr^{-1} in the top 60cm compared unfavourably with the rate of sequestration of 2.9 t yr^{-1} ha^{-1} in just the top 20cm of the soil in the secondary forest as described by (Jia et al., 2005). The rate of sequestration reported at CSiTE under prairie was better but still lower than the forest ecosystem.

3.8.3 Dryland restoration

Drylands are ‘areas where average rainfall is less than the potential moisture losses through evaporation and transpiration’ (FAO, 2004, p.7). For carbon sequestration purposes arid, semi-arid and dry sub-humid areas are considered to be drylands. Unless irrigated, hyperarid areas are not considered to be drylands (Food and Agriculture Organization of the United Nations, 2004).

Table 3.9 Dryland categories according to FAO (1993) classification and extension (UNEP, 1992)

Classification	P/PET (UNEP, 1992)	Rainfall (mm)	Area (%)	Area (10^9 ha)
Hyperarid	< 0.05	< 200	7.50	1.00
Arid	0.05 < P/PET < 0.20	< 200 (winter) or <400 (summer)	12.1	1.62
Semi-arid	0.20 < P/PET < 0.50	200–500 (winter) or 400–600 (summer)	17.7	2.37
Dry sub-humid	0.50 < P/PET < 0.65	500–700 (winter) or 600–800 (summer)	9.90	1.32
TOTAL			47.2	6.31

Source: FAO (2004, p.7)

As most carbon entering soil is labile and is quickly respired back to the atmosphere. Only about 0.4Gt of the 55Gt that enters the soil each year accumulates as recalcitrant carbon. Logically soil management must increase carbon inputs and reduce outputs (FAO, 2004). Increasing SOC enhances soil water holding capacity enabling land to better withstand drought as its presence is directly related and time taken for water to runoff. There is a similar relationship between ground cover and runoff. Evaporative losses due to bare ground are 70% higher (Neely et al., 2009).

The rangeland of the Mongolian Plateau and the steppe of Central Asia have an arid and semi-arid climate with precipitation of 250mm. Here the NPP is only 1t ha^{-1}, but there is high SOM due a high proportion of root production: 26.77 tonnes ha-1 in the top 20cm (Chuluun and Ojima, 2002). Feng et al. (2002) investigated the soil carbon of deserts and desertification-prone lands in Northern China in relation to site characteristics. Increased annual rainfall, decreased evaporation and decreased temperature all led to increased SOC.

The dynamics of soil carbon on a restored desertified environment were investigated by Su et al (2010). The authors found that rehabilitating the desertified land increased soil organic carbon, inorganic carbon and nitrogen concentrations and enhanced soil aggregation. The authors investigated changes in the soil carbon in the top 15cm of desertified land under different restoration regimes that had lasted 7 and 32 years. There were four regimes: Control (shifting sands), *Haloxylon ammodendron* Sand-fixing shrubs planted within straw checkerboards, *Populus gansuensis* shelter forest and levelled irrigated sand dune planted with Maize, cotton and wheat.

Over seven years SOC concentration in the shrub-land, forest and irrigated cropland increased by 4.1, 14.6 and 11.9 times the control and over 32 years by 11.2, 17.0 and 23.0 times the control. The increase in SOC and SIC ($CaCO_3$) and the accumulation of silt and clay assisted the formation of aggregates which mitigated wind erosion. Total soil carbon increased in the shrub-land, forest and irrigated cropland by 1.8, 10.6 and 9.4t ha^{-1} during the 7-year rehabilitation period, and 7.5, 15.4 17.3t ha^{-1} during the 32-year rehabilitation period (Su et al., 2010). It must be borne in mind that the cropland received regular inputs of manure that would bring SOM onto the site. These increases in soil carbon were only measured in the top 15cm of the soil profile.

3.9 Mycorrhizae

What mechanisms in particular are responsible for soil carbon retention and can they be manipulated to cause more carbon to be recalcitrant rather than labile?

Mycorrhizae are root-infecting fungi that form mutualistic relationships with their host plants. They infect nearly all families of flowering plant. The fungi transport nutrients to the host plant and in return receive some of the plant's products of photosynthesis. In effect the fungi vastly extend the root systems of the host plants (Smith and Read, 2008). Some mycorrhizal fungi form external sheaths around the roots of their host species – these are ectomycorrhizal fungi. Others invade the interior roots cells – endomycorrhizal fungi, also know as (vesticular) arbuscular mycorrhizal fungi (AMF) (Stamets, 2005, p.24).

AMF directly contribute to SOM. Rillig et al. (2001) found concentrations of the glycoprotein Glomalin of over 60mg cm−3 in tropical forest soils. This glycoprotein is produced by AMF hyphae. Thus carbon not derived from litter can make a substantial contribution to soil carbon and exceed the contributions of microbial biomass. Because AMF hyphal cell walls are formed of the recalcitrant carbohydrate chitin they add to the level of SOM (Zhu and Miller, 2003).

The process of soil aggregation reduces soil erosion, promotes water retention and protects SOM from mineralisation by physically preventing microorganisms from accessing it. AMF causes aggregation by producing the glycoprotein glomalin (Spohn and Giani, 2010). This substance is 30-40% carbon and is thought to play an important role in sequestration of soil carbon (Comis, 2002). Rillig et al. (2001) found that the glomalin produced by AMF contribute substantially to the SOM of tropical soils, with the glycoprotein detected at concentrations of over 60mg cm^{-3}. Rillig and Steinberg (2002) have suggested that AMF may secrete glomalin in order to modify their habitat for their own benefit as its presence correlates highly with soil aggregate water stability.

3.10 Biochar

Biochar is a carbon-rich product, similar to charcoal derived by heating biomass such as wood with a restricted oxygen supply. Addition of this substance to poor soils has numerous benefits including enhanced water and nutrient holding capacity (Lehmann and Joseph, 2009). Most importantly the carbon in biochar decomposes far more slowly than SOM so charring biomass to add to the soil diverts carbon from the rapid biological cycle into a much slower cycle (Lehmann and Joseph, 2009). Thus regular additions of recalcitrant carbon as biochar to poor sandy soil could build up soil carbon concentrations far in excess of those that could occur naturally in an ecosystem undergoing restoration.

The Amazonian dark earths known as terrapreta contained large quantities of biochar. This soil contains three times more SOM, nitrogen and phosphorus than its parent soil. A hectare of land containing terrapreta may contain 250t SOC in the top 30cm (compared to 100 in the parent material) (Glaser et al., 2001).

3.10.1 Biochar and Mycorrhizae

Reviewing the literature on the effects of biochar on mycorrhizal fungi Warnock et al (2007) described synergies. Elevated availability of soil nutrients can enhance plant growth, raise tissue nutrient concentration and facilitate higher root-colonization rates by AMF. The biochar can assist the AMF to help the plants resist pathogens. The biochar provides the mycorrhizae some protection from grazing micropredators. It also provides a refuge for bacteria that can help the mycorrhizae. In an experiment evaluating the effects of biochar on colonisation of tree roots by ectomycorrhizal fungi, significant increases were seen. However some negatives were also witnessed. One study suggested biochar limited the plants uptake of phosphate and another reported decreases in organic carbon and nitrogen in the ectomycorrhizal system.

3.10.2 How much carbon could the top 30 cm of soil of the Sahara and Arabian deserts sequester?

This thesis is concerned with carbon sequestration potential of the deserts of the MENA region that occupy 11,430,000km^2. In order to ascertain how much carbon these deserts could sequester in the top 1 metre of soil one could compare the carbon found in the deserts at present and then how much extra carbon could be sequestered if they were transformed to another type of ecosystem with human intervention such as irrigation and also how much they could sequester with further human invention such as repeated applications of biochar.

As has been seen in this chapter there is a range of estimates for the carbon contained in the soil of the world's deserts. Lioubimtseva et al. (1998) suggest that the hyperarid MENA deserts contain only 2 – 5t SOC ha $^{–1}$. The USDA (2000b); USDA (2000a) maps of organic and inorganic carbon show that most of the Sahara and Arabian deserts have SOC of under 20t ha^{-1}, with SIC carbon much higher with regions of 40 – 80 and 320 – 640t ha^{-1}. Lal (2004b), based on the USDA classification system, suggests that the Aridisols and Entisols that make up much of the deserts contain 38 and 42t SOC ha^{-1} and 290 and 124t SIC ha^{-1} respectively, with very little in the shifting sands.

Any effect to increase the SOC content of desert soils must not have a detrimental effect on the SIC of those soils. But as Lal (2003) has shown an increase in

SOC should also lead to an increase in SIC. Watson et al. (2000, p.4), cite a figure for the carbon stored in the top metre of deserts and semi-deserts of 42t ha^{-1}. This is a little higher than Lal's figures but will be used for the purpose of estimating the difference in carbon storage potential if the MENA deserts were transformed to other ecosystems as the figures for the other biomes are also supplied by Watson – see Table 3.1.

Table 3.10 shows the difference between the soil carbon in the top metre of soil of tropical the tropical biomes savannah and forest to estimate how much additional carbon could be held in the soil and vegetation if the desert was transformed to a system similar to these biomes. The table also includes the potential if biochar was added to the forest soil to bring the SOC to 250t ha^{-1} the reviewed literature does not refer to biochar being added to savannahs, so that scenario has not been investigated.

Table 3.10 Potential for MENA deserts to absorb carbon.

	Carbon stock t ha^{-1}			Potential carbon stock on 11,430,000 km^2 (Gt)		
Biome	Vegetation	Soil	Total	Vegetation	Soil	Total
Tropical savannas	29.3	117.3	146.7			
Tropical forests	120.5	122.7	243.2			
Deserts and semi-deserts	1.8	42	43.7			
Difference between savannahs and deserts	27.5	75.3	102.8	31.4	86.1	117.5
Difference between forest and deserts	118.7	80.7	199.4	135.7	**92.2**	227.9
With biochar						
Difference between forests and deserts with additional biochar	118.7	250 (169.3 biochar)	368.7	135.7	**285.8 (193.6 biochar)**	421.4

Table 3.10 shows that transforming 11,430,000km^2 of the MENA deserts to savannah or forest, with or without the use of biochar, would allow the sequestration of an extra 86.1 or 92.2Gt SOC respectively. To put these figures into context remember that to bring the atmospheric CO$_2$, level down to 350ppm requires sequestering 84.8Gt atmospheric C (Hansen et al., 2008). With the addition of biochar the soil could store 285.8Gt SOC, but the 193.6Gt of biochar would require twice that amount of vegetation to be pyrolysed.

3.11 Summary

This chapter investigated the role of soils in the global carbon cycle. It defined soil respiration rates and discussed these rates across a range of ecosystems. The chapter considered briefly SIC before moving on to examine the SOC and SIC content of the soils of the MENA region.

Soil damage was discussed to state the size of the current problem. This was followed by a consideration of soil repair to look at the potential rate of repair particularly of drylands. The importance of mycorrhiza to soil carbon sequestration and water holding was examined and the potential of biochar was briefly considered. Then the potential increase in the carbon stock of the soils was calculated if those soils were transformed into savannah or tropical rainforest – estimated to be 86.1 and 92.2Gt respectively across the MENA region. The extra possible carbon that could be sequestered into a rainforest by creating terrapreta was also calculated to raise the potential a forest soil to hold 285.8 across the MENA region.

This chapter also considered the rate of soil carbon sequestration based on figures from Jia et al. (2005). The rate of soil formation in secondary forest was 2.9t yr^{-1}ha^{-1} in the top 20cm of the soil. This slowed in subsequent years and peaked after seventeen. However the SOC was only measured in the top 20cm. Over 1,143,000,000km^2 this would sequester 3.3Gt yr^{-1} in the top 20cm of soil – equal to a third of the non-land-use-change anthropogenic carbon emissions. Over 16 years the rate would equal 2.2Gt yr^{-1}. If biochar were applied to soil on a large scale, it would need to be produced from vegetation grown on the same site and that would imply a large reduction in the amount of carbon sequestered a year if it were produced from timber that could otherwise be stored or used. At least 50% would be re-released as CO_2 (Lehmann et al., 2006).

In order to move the carbon from the atmosphere to the soil requires growing vegetation. This was discussed in Chapter 2. Vegetation requires water and the premise of this thesis is that this water will be provided by desalination. This will be the topic in Chapter 4.

3.11.1 Key data from Chapter 3

Potential C difference after transformation of biome from desert to forest, with and without biochar.

Veg^n (GtC)	Soil (GtC)	Total (GtC)
135.7	**92.2 GtC**	**227.9**
135.7	**285.8 (193.6 in biochar)**	**421.4**

Calculated C in biomes from source data in: Watson et al. (2000, p.4) and biochar information in: Glaser et al. (2001).

C sequestration in top 20 cm soil during desertification restoration.

3.3 GtC yr^{-1} averaged over first 8 years.

2.2 Gt yr^{-1} averaged over first 16 years.

Calculated from source data in: Jia et al. (2005)

Box 3.1 Key data from Chapter 3

Chapter 4 Desalination

4.1 Introduction

Calculations in Chapter 2 indicate that the 11,430,000km^2 of MENA deserts planted with *Eucalyptus grandis* x *urophylla* and irrigated at a rate of 9,000 – 10,000m^3 water ha^{-1}yr^{-1} could sequester 8.7 – 16.2GtC yr^{-1}. This would require 10,287 – 11,430km^3 water yr^{-1}. Chapter 4 will investigate the potential for water to be desalinated by CSP in the MENA region and whether it can meet this requirement. First this chapter will discuss the predicted water deficit in the MENA region as investigated by the DLR, as this deficit must be addressed prior to irrigating the MENA deserts.

4.1.1 Water

From Table 4.1 it can be seen that the world contains an estimated 1,386,000,000km^3 of water. Unfortunately very little of this water is freshwater, and most freshwater is inaccessible. For example, 70% is locked in glaciers.

Table 4.1 Hydrological Cycle

	Volume (000 km^3)	Total Water (%)	Fresh Water (%)
Total water	1,386,000	100%	
Total freshwater	35,000	2.5%	100%
World oceans	1,340,000	96.7%	
Saline groundwater	13,000	0.9%	
Fresh groundwater	10,500	0.8%	30%
Antarctic glaciers	21,600	1.6%	61.7%
Greenland glaciers	2,340	0.2%	6.7%
Arctic islands	84	<0.01%	0.2%
Mountain glaciers	40.6	<0.01%	0.1%
Ground ice/permafrost	300	<0.01%	0.9%
Saline lakes	85.4	<0.01%	
Freshwater lakes	91	<0.01%	0.3%
Wetlands	11.5	<0.01%	<0.1%
Rivers	2.12	<0.01%	<0.1%
In the atmosphere	12.9	<0.01%	<0.1%

Source: Shiklomanov (1993) in Gleick et al. (2008, p.6)

4.2 MENA Water deficit

The DLR study, AQUA-CSP (Trieb et al., 2007), evaluated the use of CSP for large-scale seawater desalination for the MENA region's urban centres. Desalination is vitally important in the region as population growth and over extraction of non-renewable groundwater sources are predicted to cause severe shortages in the near future (Trieb et al., 2007). The countries involved in the study are listed in Table 4.2 and shown graphically in Figure 4.1.

Table 4.2 Countries in the DLR AQUA-CSP Study

North Africa	Middle East	
Morocco	Iran	Saudi Arabia
Algeria	Iraq	Kuwait
Tunisia	Syria	Bahrain
Libya	Jordan	Qatar
Egypt	Lebanon	United Arab Emirates
	Israel	Oman
	Palestine	Yemen

Source: Trieb et al. (2007)

Figure 4.1 Map showing the MENA nations included in the DLR AQUA-CSP Study.

Source: User created map based on Canuckguy (2010). Data source: Trieb et al. (2007)

Currently 85% of the freshwater consumption in MENA goes to agriculture, but this is expected to drop to 65% by 2050, not because usage is predicted to fall, but rather because of greater industrial and municipal consumption. Water use is predicted to grow from 270km^{3}yr^{-1} in the year 2000 to about 460km^{3}yr^{-1}. Efficiency measures such as enhanced distribution, irrigation systems and reuse of wastewater are expected to account for 50% of the freshwater deficit, but overuse of groundwater is still expected to grow from 50km^{3}yr^{-1} to 150km^{3}yr^{-1} in 2050 (Trieb et al., 2007, p.5). Table 4.3 shows the predicted freshwater demand and deficit in the MENA region in 2050 based on DLR data.

Table 4.3 Predicted freshwater demand and deficit in the MENA region 2050 based on the AQUA-CSP study.

Region	Predicted demand for freshwater in 2050 (km^{3}yr^{-1})	Predicted deficit of freshwater in 2050 (km^{3}yr^{-1})
North Africa	184	77
Middle East	278	73
Total	**462**	**150**

Source: (Trieb et al., 2007, p.88)

4.3 Desalinating Sea Water using renewable energy

The DLR examined commercially available desalination technologies that can be combined with CSP on a large scale. The two most promising were the thermal distillation process Multi-Effect Desalination (MED) and mechanical membrane separation process Reverse Osmosis (RO) (Trieb et al., 2007, p.22).

4.3.1 Multi Effect Desalination

MED is so called because it consists of multiple stages or ‘effects’. Each effect takes place within a separate chamber containing evaporator tubes. The evaporator tubes in the first chamber are filled by steam from a boiler. Saline feed-water is preheated and then distributed on the evaporator tubes in the first chamber. Some of the water evaporates and the steam flows into the evaporator tubes of the next chamber. Here more saline feed-water is distributed on the surface of this second set of evaporator tubes and some of that water evaporates and flows into a third chamber. Each stage uses energy in the steam produced from the previous stage. MED plants have a typical heat consumption of 190,000-390,000 kJ/tonne and an electricity consumption of 1.5 - 2.5 kWhm^{-3} independent of water quality (Trieb et al., 2007, p.17).

4.3.2 Reverse Osmosis

During the process of osmosis water moves across a selectively permeable membrane from an area with low solute concentration to an area of high solute concentration. RO uses the application of pressure to reverse this flow and cause freshwater to move across a membrane leaving the salt molecule behind. To apply this pressure requires the use of energy, which is supplied by electricity. The water also requires pre-treatment to remove bacteria, algae, particulate and organic material. The amount of electricity required is related to the salt concentration of the feed water. The average amount of electricity is 4.2 kWh m^{-3} water produced but can range from 2.5 to 7 kWh m^{-3} (Trieb et al., 2007, p.22).

The Ashkelon Seawater Reverse Osmosis (SWRO) plant in Israel is the largest in the world. It has a capacity of 100,000,000m^{3} yr^{-1}. The electricity consumption is less than 4kWh m^{-3} water (Water-Technology, 2010a). This plant is powered by fossil fuel.

Table 4.4 Comparison of desalination treatments Multi-Effect Desalination (MED) and Reverse Osmosis (RO).

Process	MED	RO
Type of energy used	Thermal	Mechanical
State of the Art	Commercial	Commercial
Heat Consumption (kJ/kg)	145 – 390	--
Electricity Consumption (kWh/m³)	1.5 - 2.5 Not including power losses induced by cogeneration due to increasing outlet temperature at the turbine.	2.5 - 7
Plant Cost (US$/m³/d). Increases with product water quality and energy efficiency	900 – 1700	900 -1500
Conversion Freshwater / Seawater	23 – 33%	20 - 50%
Max. Top Brine Temperature (°C)	55 – 70	45 (max)
Reliability	very high	moderate (for seawater)
Maintenance (cleaning per year)	1 – 2	several times
Pre-treatment of water	Simple	demanding
Operation requirements	Simple	demanding
Product water quality (ppm)	< 10	200 - 500

Source: Trieb et al. (2007, p.22)

It can be seen from Table 4.4 that there are advantages and disadvantages to both methods.

Only about 25% of the solar energy collected by CSP units is converted into electricity (CSP will be covered in more detail in Chapter 5). If combined with seawater desalination in MED systems another 50% of the energy can be used for desalination. So for desalination plants that can be co-sited with coastal CSP plants, MED is a good method to use. However, the major advantage of RO is that the electricity can be supplied to the desalination plant from anywhere with a grid connection (Trieb et al., 2007). To desalinate the amount of water that will be needed to irrigate large areas of desert electricity will need to be generated by CSP plants located inland and transmitted to coastal RO facilities. Furthermore after reviewing several renewable-energy-driven desalination technologies, researchers, Eltawil et al. (2009) concluded that RO is becoming the technology of choice with continued advances being made to reduce the total energy consumption and lower the cost of water produced.

4.4 Meeting the MENA water deficit

Table 4.5 shows the desalination requirement and subsequent energy requirement to produce the water to bridge the predicted deficit of the MENA region in 2050.

Table 4.5 Desalination requirement and energy use of the MENA region in 2050

	Desalination requirement 2050 (km^3yr^{-1})	Energy for Desalination 2050 ($TWh\ yr^{-1}$) ($3.4kWhm^{-3}$ of water in cogeneration)
North Africa	84	287
Middle East	75	257
Total	**159**	**545**

Source: Trieb et al. (2005b, pp.144 and A-1 - A-25). Individual nations are shown in Appendix F

Table 4.5 shows that to meet the predicted water deficit in 2050 in the MENA region using the DLR's scenario will require 545 TWh of electricity to desalinate the water in cogeneration at a rate of 3.4kWh m^3. But to desalinate seawater with that efficiency requires sufficient coastal potential. The coastal potential is the electricity that could be generated from sites that meet the criteria for economic potential (see section 5.4.1) and are within 20 vertical metres of sea level (Trieb et al., 2005b, p.61). Table 4.6 compares the CSP coastal potential of the MENA region to the energy requirement for desalination.

Table 4.6 Desalination requirement compared to coastal potential

	Predicted desalination requirement 2050 (km^3yr^{-1})	Energy for desalination 2050 ($TWh\ yr^{-1}$)	Coastal potential ($TWh\ yr^{-1}$)	Coastal potential **NOT** required for desalination ($TWh\ yr^{-1}$)	%age coastal potential required for desalination
North Africa	84	287	1,703	1416	16.9%
Middle East	75	257	4,022	3,765	6.4%
Total	**159**	**545**	**5,725**	**5,180**	**9.5%**

Source: Coastal Potential: Trieb et al. (2005b, pp.A-1 - A-25)

4.4.1 Additional potential

It can be seen from Table 4.6 that overall 9.5% of the coastal potential is required to supply the electricity required to desalinate enough water to meet the freshwater shortfall in the MENA region in 2050.

4.4.1.1 Coastal

There is an additional coastal potential of 5,180TWh yr^{-1} available in the MENA region that is not required to alleviate the overexploitation of groundwater. Produced at the same rate 3.4kWh m^{-3} this could desalinate an additional 1,524km^3 freshwater yr^{-1}.

4.4.1.2 Inland

In addition to the coastal potential of the MENA region, the economic potential that is not used to produce electricity for the EU-MENA region (this will be investigated in Chapter 5) could be used to produce electricity for straight RO desalination without any cogeneration with MED. In this case the electricity requirement for each m^3 of water desalinated would be higher.

The potential would depend on the efficiency of RO desalination plant. The range is 2.5 – 7KWh m^{-3} (Trieb et al., 2007) with 4.2kWh as a typical reference value (Tahri, 2001). Calculations in this thesis will use the reference figure of 4.2kWh. The actual energy requirement will be site specific depending on the salinity of the source water and will require further research.

4.4.1.3 Other Nations

The five North African countries investigated by the DLR – Morocco, Algeria, Tunisia, Libya and Egypt – are not the only nations with land in the Sahara desert, or coastlines suitable for desalination plants. There are several other Saharan countries below the NA nations with land that may be suitable for siting CSP units or RO plants. Western Sahara and Mauritania’s combined coastline of 1,864km (CIA, 2010a) and additionally much of Senegal’s 531km of coastline may be suitable for integrated desalination and CSP units. Research, similar to that performed by the DLR in the MENA nations is required to assess the economic, and where appropriate the coastal, potential of the other Saharan nations. Similarly, these nations should also be researched for possible future freshwater deficit, as any deficit should be addressed before water could be used for desalination. Section 5.6 will examine the predicted growth in electricity requirements of the MENA nations. The electricity requirements of other nations participating in a project to irrigate the Sahara should also be assessed. Section 5.8.1 provides an estimate of the future electricity requirement of sub-Saharan Africa if the region follows a similar development path to the MENA region.

4.4.1.3.1 The Great Green Wall

There are eleven nations participating in ‘The Great Green Wall’ tree-planting project to attempt to halt the spread of the Sahara desert. These countries are Senegal, Mauritania, Mali, Burkina Faso, Niger, Nigeria, Chad, Sudan, Eritrea, Ethiopia and Djibouti. This project aims to plant a wall of trees 7000km long and 15km wide across the bottom of the Sahara desert (Grande Muraille Verte, 2009a). This barrier marks the southern border of the Sahara desert and the countries involved illustrate the number of other African nations that could be involved in a project to irrigate the Sahara desert. Each country will require a full assessment in terms of CSP and RO potential and electricity and water needs as described in section 4.4.1.3 above.

Figure 4.2 Map showing the MENA nations included in the DLR Study (dark yellow) nations participating in the Great Green Wall project (light yellow) and the path of the Great Green Wall (dark green line). The grey nation below Morocco is Western Sahara – a disputed state.

Source: User created map based on Canuckguy (2010). Data sources: (Trieb et al., 2007; GGW, 2009b)

4.5 Other electrical costs and losses

While the potential electricity required for desalination could be calculated using a figure of 4.2kWh m^{-3} of water, this does not take into account certain other costs and losses. Freshwater produced by desalinating seawater at the coast must be pumped inland often against gravity. Ornstein et al. (2009) estimated that the energy to pump water from sea level to the average elevation of the Sahara (450m) would be 2.46kWh m^{-3}. The average elevation of the Arabian Peninsula is around 1,000m (Hansen et al., 2007), which would result in average water pumping costs of 5.47kWh m^{-3}. However much of the peninsula has lower elevations. The great Rub' al-Khali desert has a surface elevation in the far southwest of 800m, which declines evenly over 100km to near sea level in the northeast (WWF, 2001). However to avoid speculating and possibly underestimating the requirements the figure of 1,000m average elevation for the Arabian Desert will be used. This means that the average water pumping costs for each m^3 of water in both deserts, based on land area and average elevation, is 3.07kWh m^{-3} and this will need to be added to the electrical cost of desalination.

There are also electrical losses to consider. These amount to 10-15% when transmitting electricity over HVDC cables 1,000s of kilometres from MENA to Europe

(Trieb et al., 2006). These figures should be minimised within the MENA region itself. The figures would not apply to the water desalinated in co-generation at the coast and those units supplementing the coastal potential by RO could be located as close to the coast as possible. There could be CSP stations specifically for pumping the water located throughout the deserts to minimise losses. This thesis will estimate that average losses of 5% would be incurred. More research is required.

4.6 Electricity required

The calculations in Box 4.1 estimate the electricity required to irrigate 11,430,000km^2 of MENA deserts with 10,287 – 11,430km^3 water yr^{-1}.

Water required to irrigate 11,430,000km^2 of MENA deserts = 10,287 – 11,430km^{3}yr^{-1}.

Coastal potential NOT required to meet future water deficit in MENA region = 1,524km^3 of freshwater yr^{-1}

Electrical requirement of ‘excess’ coastal potential = 6.62kWh m^{-3} of which 3.4kWh m^{-3} for desalination + 3.22kWh m^3 for distribution (including 5% electrical losses for distribution but not desalination)

Thus electricity required to desalinate and distribute the first 1,524km^3 of freshwater = **10,089TWh yr^{-1}**.

Water to be desalinated by RO = 8,763 – 9,906km^3 yr^{-1}.

Electrical requirement for RO = 7.63kWh m^{-3} of which 4.2kWh m^{-3} for desalination + 3.07kWh m^{-3} for distribution and 5% electrical losses overall.

Electricity required to desalinate and distribute 8,763 – 9,906km^{3}yr^{-1} = **66,862 – 75,583TWh yr^{-1}.**

Total electrical requirement 76,951 – 85,672TWh yr^{-1}.

Box 4.1 Total electrical requirement to desalinate the water to irrigate 11,430,000km^2 of MENA deserts

4.7 Land required for Reverse Osmosis

The Ashkelon SWRO has a capacity of 100,000,000m^{3}y^{-1} and a footprint of 75,000m^2 (300m x 250m). (Water-Technology, 2010a). This is equivalent to 1,333m^3 water yr^{-1} being produced for each m^2 of plant or 1.333km^3 for each km^2. Based on a linear extrapolation of plant footprint size, to desalinate 10,287 - 11,430km^{3}y^{-1} water would require RO plants covering 7,715 - 8,573km^2. This linear relationship may not be accurate and further research is needed, but based on these figures this thesis will assume that the RO plants would cover a negligible percentage of the land area of the MENA deserts.

4.8 Summary

This chapter has investigated the desalination technologies and the predicted future freshwater deficit in the MENA region. It has looked at the coastal potential of the region to meet the shortfall in freshwater and estimated the additional water that could be made available to irrigate the MENA deserts.

The chapter has estimated the amount of electricity that would be required to produce enough water to irrigate the whole of the MENA deserts: 76,951 – 85,672TWh yr^{-1}. But how much electricity could the deserts of the MENA region produce using CSP? That will be investigated in the next chapter.

4.8.1 Key data from Chapter 4

Electricity requirement to desalinate and move water **76,951 – 85,672TWh yr^{-1}.**

(10,089TWh yr^{-1} is for the first 1,524km^3 water at 6.62kWh m^{-3} water and 66,862 – 75,583TWh yr^{-1} for the remaining 8,763 – 9,906 $km^3 yr^{-1}$ at 7.63kWh m^{-3}.)

Calculated from source data in: Trieb et al. (2007) with input from data in: Ornstein et al. (2009; Trieb et al. (2005b); Trieb et al. (2006); Hansen et al. (2007)

Estimated land area for RO **7,715 – 8,573km^2.**

Calculated from source data in: Water-Technology (2010a) Based on the figures for the Ashkelon SWRO

Box 4.2 Key data from Chapter 4

Chapter 5 Electricity generation by concentrating solar power

5.1 Introduction

Chapter 5 discusses the Desertec foundation (Wolff, 2010) and the work that they commissioned the DLR to undertake to assess the potential of the MENA region to generate electricity by CSP. The chapter discusses the DLR's predictions for electricity use in 2050 in the MENA region and the electricity it predicts will be exported to Europe in its renewable energy scenario. The chapter also estimates Sub-Saharan Africa's electrical requirement in 2050 and estimates how much land will need to be set aside for CSP to meet these needs. The chapter assesses whether the MENA deserts could provide this electricity and the 76,951 – 85,672TWh electricity yr^{-1} required to desalinate 10,287 – 11,430km^3 water. The total land area required to host all the CSP units will be estimated as this will reduce the total area available for growing vegetation.

5.2 Desertec

The DESERTEC foundation, an initiative of the Club of Rome, is a network of collaborating politicians, scientists and engineers amongst countries in the EU-MENA region. The foundation aims to provide renewable energy for the region based on economic cooperation (Wolff, 2010). The foundation aims to exploit the potential of the MENA deserts for the production of solar electricity and integrate it into the electricity supply of nations in the EU-MENA region, transmitting via a HVDC supergrid (Wolff, 2010). Electricity from other renewable sources throughout the region would also be integrated into the supergrid (Trieb et al., 2006).

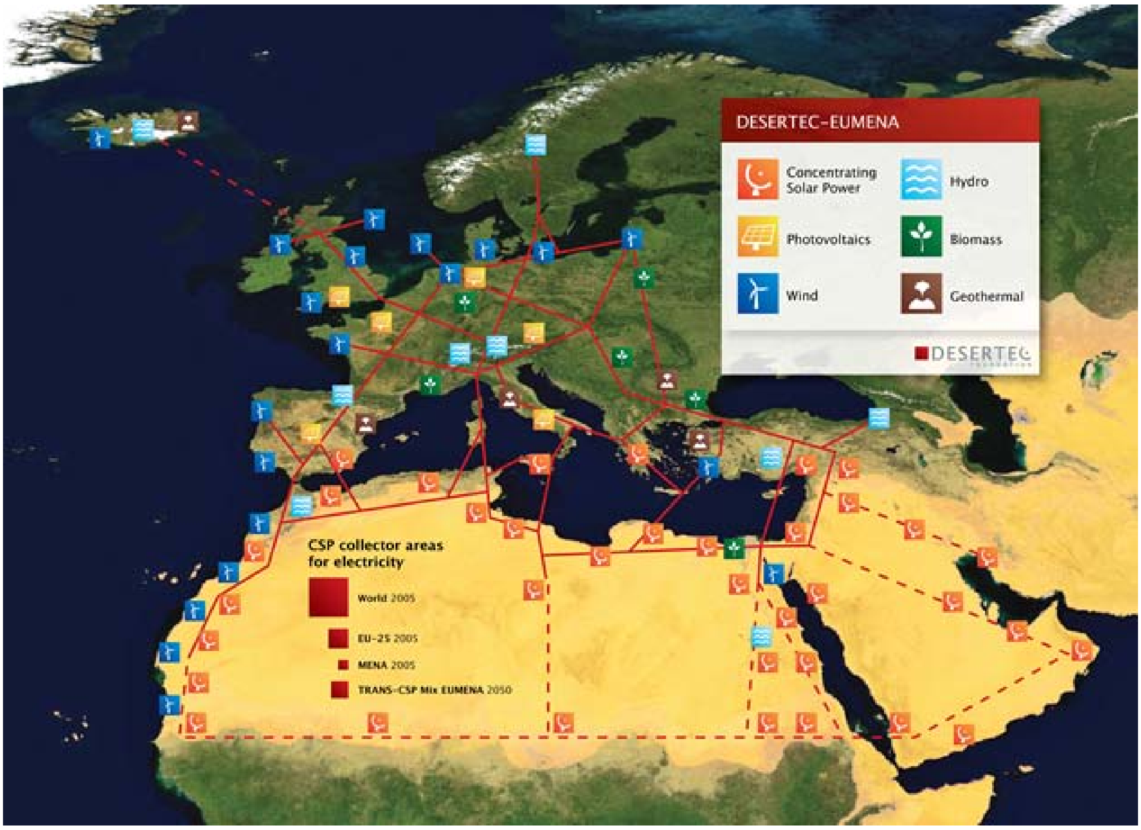

Figure 5.1 DESERTEC EU-MENA Map: Sketch of possible infrastructure for a sustainable supply of power to the EU-MENA region

Source: (Desertec Foundation, 2010)

5.2.1 The DLR studies

The DLR was commissioned to conduct three studies:

- *AQUA-CSP* (Trieb et al., 2007) discussed in Chapter 4.
- *MED-CSP*: The potential of the MENA region to generate renewable energy mostly by CSP (Trieb et al., 2005b).
- *TRANS-CSP*: European potential to generate electricity, supplemented with CSP generated electricity from the MENA region (Trieb et al., 2006).

The studies concluded that by importing 700TWh yr^{-1} in 2050 of CSP generated electricity in combination with other renewable technologies the nations in the *TRANS-CSP* (mainly European) study could cut CO_2 emissions from electricity generation to 25% of year 2000 levels by 2050, and phase out nuclear power at the same time (Trieb et al., 2006, p.2). The nations in the *MED-CSP* study, despite large increases in electricity consumption, could cut CO_2 emissions from electricity production to 60% of year 2000 levels by 2050 (Trieb et al., 2005b, p.17). The countries included in the DLR studies included most EU and the MENA nations – See Figure 5.2 and Appendix G.

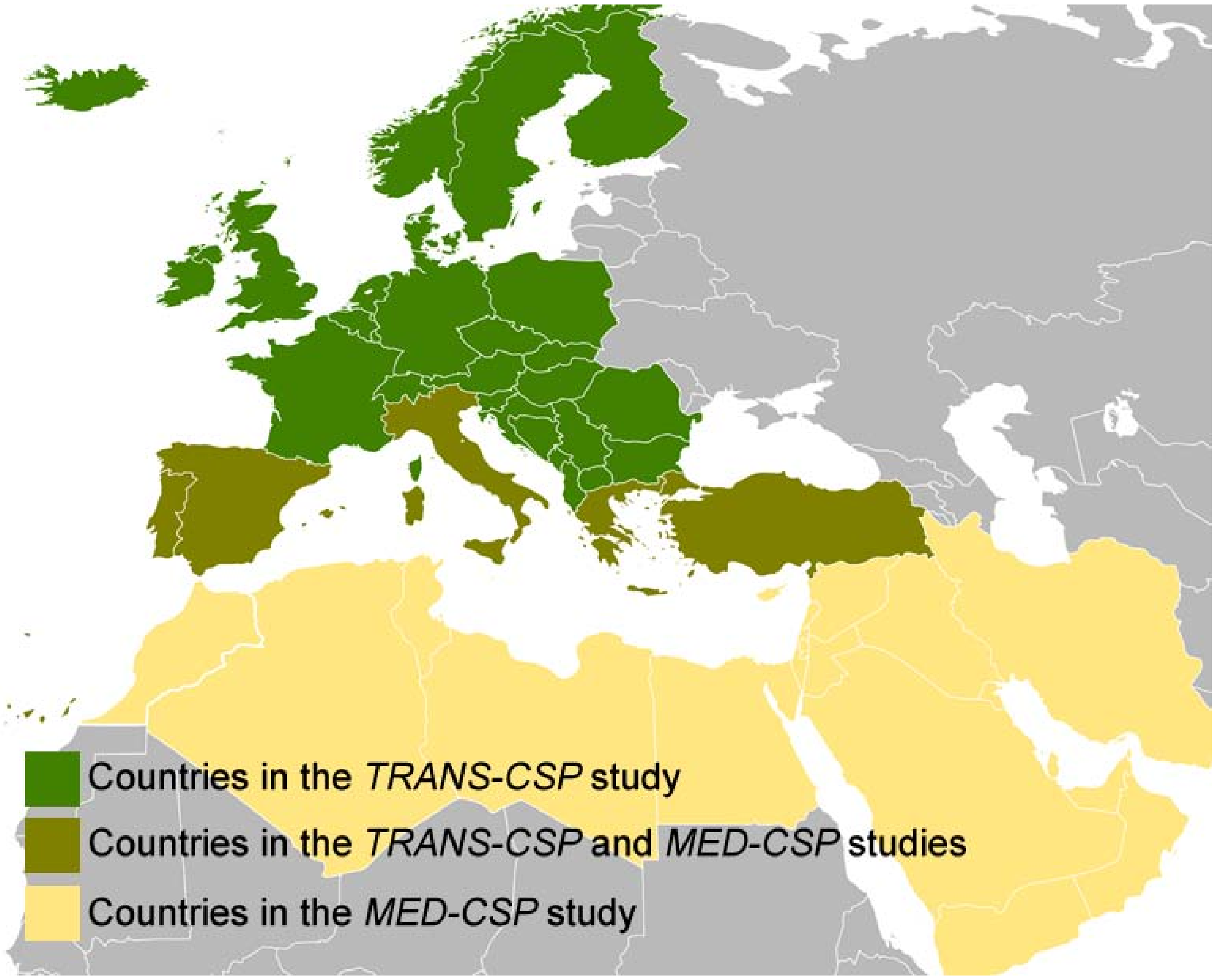

Figure 5.2 Countries in the *TRANS-CSP* and *MED-CSP* studies

Source: User created map based on Canuckguy (2010). Data sources: (Trieb et al., 2005b; Trieb et al., 2006)

5.3 Concentrating Solar Power

Concentrating Solar Power (CSP) line-focusing units are renewable energy producing devices of simple design: mostly constructed of steel and glass. They use mirrors to focus sunlight onto steel absorber tubes to concentrate the heat. The units track the sun and the absorber tube, which contains either synthetic oil or stream, transfers the heat to a turbine to produce electricity. Surplus energy can be transferred to heat storage, such as molten nitrate salt to be used when there is insufficient sunlight (Trieb et al., 2005b, pp.40-41).

The older CSP technology uses parabolic troughs with concave mirrors to track the sun. The newer devices called Linear Fresnel are of a simpler, cheaper design where the parabolic shape is split into several flat pieces that are fitted onto horizontal bars that can be used to move each segment to track the sun. The absorber tube is fixed in the centre of the solar field above the mirrors and remains stationary (Pitz-Paal, 2008a; Pitz-Paal, 2008b).

Figure 5.3 Parallel trough and linear Fresnel CSP units showing sunlight focussing on the absorber tube.

Source: Pitz-Paal (2008a)

The Fresnels are one-fifth the weight of parabolic troughs m^{-2} and do not need to be fitted on central pylons. They contain less material to construct and hence have lower embodied energy. The four corners of the Fresnel's support structure are simply screwed into the ground (Trieb et al., 2007, pp.30-31).

Although the Fresnel system has an optical efficiency per unit of the collector field of about 75% of the parabolic trough, the overall land use is much more efficient as the mirrors can cover over 80% of the land as opposed to the 30% of the parabolic trough. Overall the Fresnel system has twice the energy yield m^{-2} than a parabolic trough. Other major advantages of the Fresnel system are that vegetation can be grown in partial shade below it, with the mirrors acting like louvre blinds and the system can be integrated into terrain that is unsuitable for parabolic trough systems (Trieb et al., 2006, pp.30-31). Farming below Fresnels could be a serious benefit for food production in the desert areas and will be considered in section 7.3.4.

Figure 5.4 Energy production above and horticulture underneath a linear Fresnel collector field

Source: Collector field by Solarmundo, greenhouse visualisation by DLR (Trieb et al., 2005b, pp.A-79)

5.3.1 Direct Solar Irradiation (DNI)

DNI is a measure of how much solar energy an area of land receives. It is measured in KWh $m^{-2}yr^{-1}$. A higher DNI means more energy is available for harvest by CSP. The hot deserts of the world have the highest annual DNI and are the most suitable locations for CSP as they also tend to be the least forested, farmed and inhabited areas (Trieb et al., 2009). Figure 5.5 illustrates worldwide DNI.

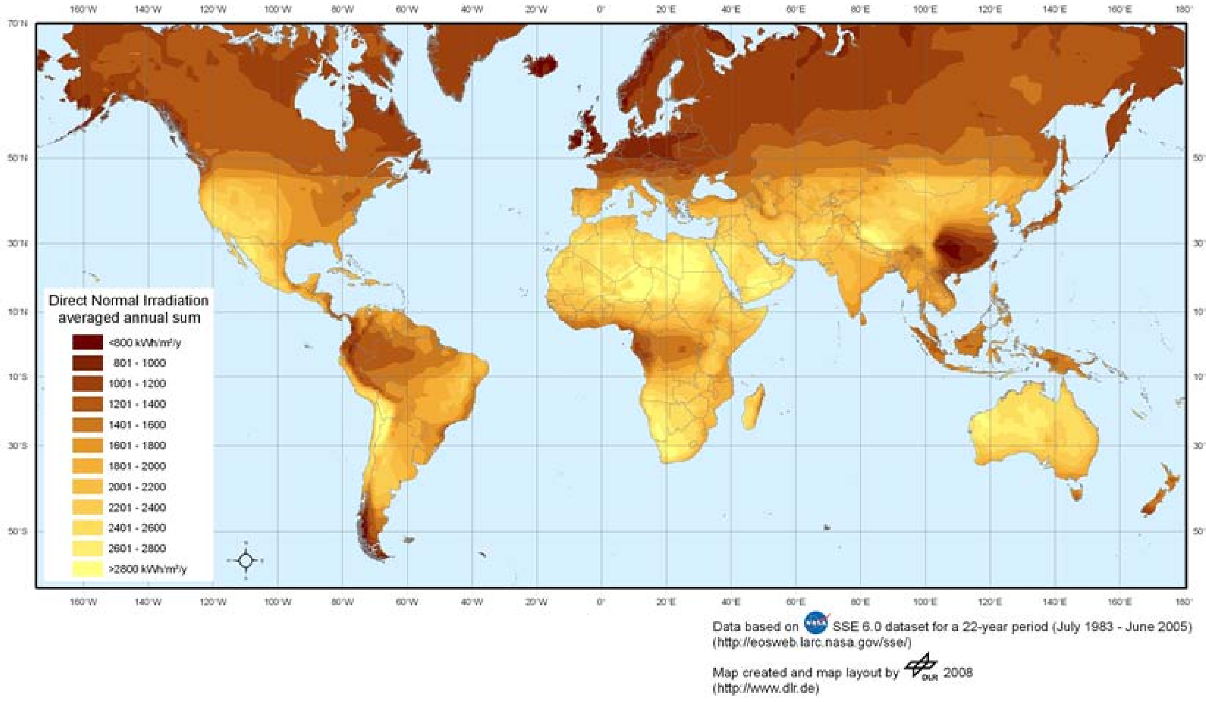

Figure 5.5 World Direct Normal Irradiation

Source: Trieb et al. (2009)

Trieb et al quantified the land area that falls within various DNI classes above the economic threshold for CSP (2000 KWh $m^{-2}yr^{-1}$) for various regions of the world. Values for Africa and EU-MENA are shown in Table 5.1. Africa has 500 times more potential land than the EU.

Table 5.1 Area of land within various DNI classes in Africa, the Middle and the EU

DNI Class	Africa	Middle East	EU27+
KWh $m^{-2}yr^{-1}$	km²	km²	km²
2000-2099	1,082,050	36,315	9,163
2100-2199	1,395,900	125,682	5,016
2200-2299	1,351,050	378,654	6,381
2300-2399	1,306,170	557,299	1,498
2400-2499	1,862,850	633,994	800
2500-2599	1,743,270	298,755	591
2600-2699	1,468,970	265,541	257
2700-2800+	2,746,100	292,408	270
Total [km²]	12,956,360	2,588,648	23,975

(Trieb et al., 2009)

5.3.1.1 Land Use Efficiency of CSP units

The land use efficiency (LUE) of CSP units is related to the Solar Electric Efficiency (SEE) and Land Use Factor (LUF). There is a range of values for both SEE and LUF for Parabolic Trough and Linear Fresnel CSP units, which leads to a range of values for LUE (Trieb et al., 2009). These are shown in Table 5.2.

Table 5.2 Land Use Efficiency for CSP units

Collector & Power Cycle Technology	SEE = Annual Direct Irradiance on Aperture / Annual Net Power Generation		LUF = Total Land Area Required / Aperture Area of Reflectors		LUE = SEE x LUF		
	Low value	High value	Low value	High value	Low value	High value	Middle value
Parabolic Trough	11%	16%	25%	40%	2.7%	6.4%	**4.5%**
Linear Fresnel	8%	12%	60%	80%	4.8%	9.6%	**7.2%**

Source: Trieb et al. (2009)

5.4 Theoretical potential for generating electricity

The amount of electricity that can be generated by CSP units per unit area can be calculated from the LUE and the DNI (Trieb et al., 2009). Combining values from Tables 5.1 and 5.2 the electricity producing potential for the various regions of the earth can be calculated. Table 5.3 uses mid-range value for linear Fresnels and parallel troughs and the mid-point DNI of the various regions of Africa and the Middle East.

Table 5.3 Electricity that can be generated in Africa and the Middle East by a Linear Fresnel system with a LUE of 7.2% and a Parabolic Trough system with a LUE of 4.5.

	TWh yr^{-1}		TWh yr^{-1}		TWh yr^{-1} Km^{-2}	
	Africa		Middle East			
Mid-Point TWh yr^{-1} km^{-2}	7.2% LUE	4.5% LUE	7.2% LUE	4.5% LUE	7.2% LUE	4.5% LUE
2.05	159,711	99,819	5,360	3,350	0.1476	0.09225
2.15	216,085	135,053	19,456	12,160	0.1548	0.09675
2.25	218,870	136,794	61,342	38,339	0.162	0.10125
2.35	221,004	138,127	94,295	58,934	0.1692	0.10575
2.45	328,607	205,379	111,837	69,898	0.1764	0.11025
2.55	320,064	200,040	54,851	34,282	0.1836	0.11475
2.65	280,279	175,175	50,665	31,666	0.1908	0.11925
2.75	543,728	339,830	57,897	36,185	0.198	0.12375
Total	**2,288,348**	**1,430,218**	**455,703**	**284,814**		

Source: Calculated from figures provided by Trieb et al. (2009)

5.4.1 Area of desert suitable for CSP.

Unfortunately not all areas that have high DNI are suitable for the placement of CSP units for various reasons such as sloping terrain, sand dunes and urban settlements. The suitable areas were investigated by the DLR (Trieb et al., 2005a). Trieb et al. (2009) identified those locations where sufficiently high DNI coincides with suitable land area. Figure 5.6 illustrates these suitable areas graphically and also hints at the potential for those northern African nations not included in the DLR studies to generate electricity.

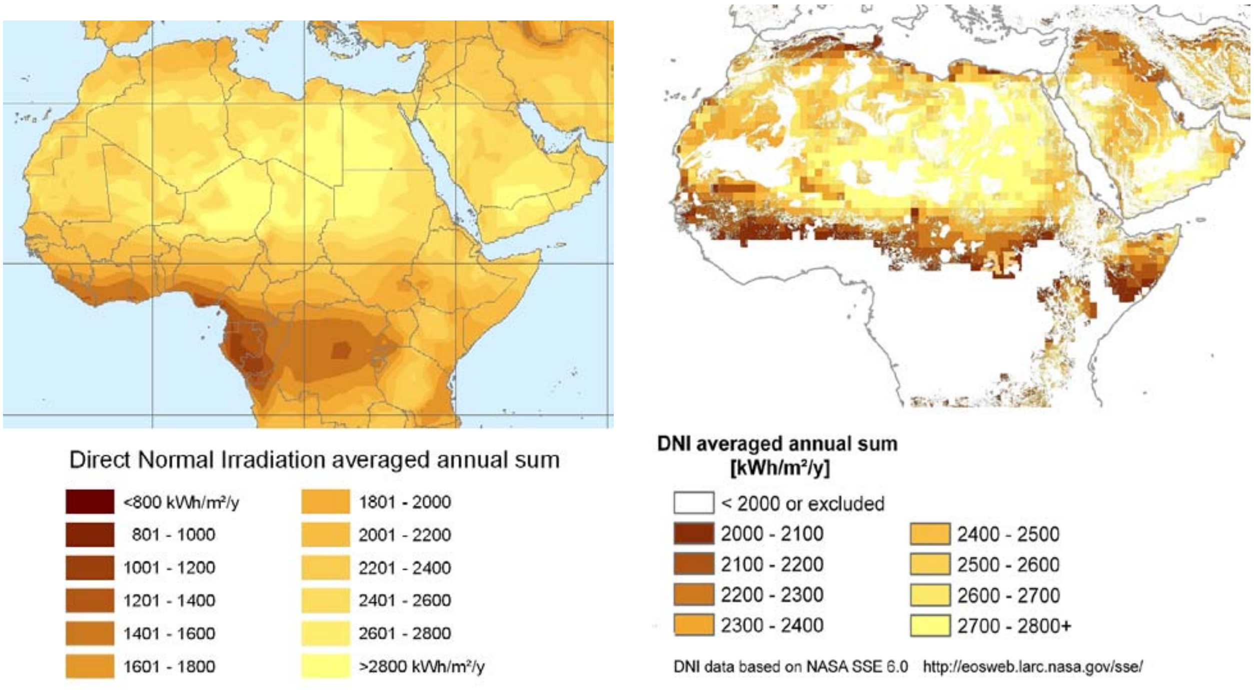

Figure 5.6 Direct Normal Irradiation and areas suitable for positioning CSP units in the MENA region.

Source: (Trieb et al., 2009)

5.5 Potential for the MENA deserts to generate electricity

The DLR calculated the technical, economic and coastal potential of the individual nations in the study. The economic potential is the amount of electricity that could be generated where direct normal irradiance is above 2000kWh m^{-2} yr^{-1}, whilst the coastal potential is that which could be generated within 20 vertical metres of sea level. It is technically possible for CSP generation to take place at a lower DNI: above 1800kWh $m^{-2}yr^{-1}$. This is the technical potential (Trieb et al., 2005b, p.61). The DLR also used a DNI conversion factor of 4.5% to convert DNI to TWh yr^{-1} (Trieb et al., 2009, p.8). This value is more conservative than the figure of 7.2%, as the DLR used the proven technology of parabolic troughs rather than linear Fresnel in their calculations. Values for the individual nations can be found in Table 5.4.

Table 5.4 Technical, Economic and Coastal potential of countries in the MENA region

Country	Technical Potential (TWh yr^{-1})	Economic Potential (TWh yr^{-1})	Coastal Potential (TWh yr^{-1})
Morocco	20,151	20,146	300
Algeria	169,440	168,972	57
Tunisia	9,815	9,244	352
Libya	139,600	139,477	498
Egypt	73,656	73,656	496
Total North Africa	**412,662**	**411,495**	**1,703**
Oman	20,611	19,404	497
Kuwait	1,525	1,525	134
Qatar	823	792	324
Saudi Arabia	125,260	124,560	2,055
UAE	2,078	1,988	538
Yemen	5,143	5,100	390
Bahrain	36	33	21
Israel	318	318	2
Jordan	6,434	6,429	0
Lebanon	19	14	0
Syria	10,777	10,210	0
Iraq	30,806	28,647	61
Total Middle East	**203,830**	**199,020**	**4,022**
Total MENA	**616,492**	**610,515**	**5,725**

Source: Trieb et al. (2005b, pp.A-1 - A-25)

It can be seen from Table 5.4 that the total economic potential of the MENA region far exceeds the 76,951 – 85,672TWh yr^{-1} required to irrigate the whole of the MENA deserts. Indeed Algeria alone has twice the necessary economic potential: 168,972TWh yr^{-1}.

5.6 Electricity requirement in the EU-MENA region in 2050

The *CSP-MED* report predicts that the electricity requirement of the MENA region will grow to 4100 TWh yr^{-1} in 2050 (Trieb et al., 2005b, p.71) and under the *CSP-TRANS* scenario only an additional 700TWh yr^{-1} would be required to be transported to Europe (Trieb et al., 2006, p.2) giving a total figure of 4,800TWh yr^{-1}. Table 5.4 shows that Tunisia alone has an economic potential of nearly double this figure.

5.7 Land area needed to generate electricity for desalination

How much land area would be required to generate the 76,951 – 85,672TWh yr^{-1} calculated in section 4.6 needed to desalinate the water to irrigate the MENA deserts?

When assessing technical, economic and coastal potential (Table 5.4) the DLR used a factor of 4.5% to convert DNI to TWh yr^{-1} (Trieb et al., 2009, p.8) based on parallel troughs. The economic potential for DNI is set at 2 TWh km^{-2} yr^{-1} (2000kWh $m^{-2}yr^{-1}$) and can exceed 2.8TWh $km^{-2}yr^{-1}$ in the MENA region – see Table 5.4. This thesis will assume a value of 2.4TWh $yr^{-1}km^{-2}$ in order to calculate land area for CSP units.

Mean DNI falling on 1 km^2 of land in the MENA region = 2.4TWh yr^{-1}

Mean LUE for parallel troughs = 4.5%.

Electricity that can be generated by 1 km2 land covered in parallel troughs = 0.108 (4.5%*2.4) TWh km^2yr^{-1}.

Land required to produce 76,951 – 85,672 TWh electricity yr^{-1} using **parallel troughs = 712,509 – 793,259km^2.**

Mean LUE for linear Fresnels = 7.2%.

Electricity that can be generated by 1km^2 land covered in linear Fresnels = 0.173 (7.2%*2.4) TWh km^2yr^{-1}.

Land required to produce 76,951 – 85,672 TWh electricity yr^{-1} using **linear Fresnels = 444,803 – 495,214 km^2.**

Box 5.1 Land required to generate the electricity needed to irrigate the MENA deserts using parallel troughs of linear Fresnels

Box 5.1 shows that 444,803 – 495,214km^2 of land in the MENA deserts covered in linear Fresnels could desalinate enough seawater to irrigate the MENA deserts. 712,509 – 793,259km^2 of land dedicated to parallel troughs would be needed.

5.8 Land area needed for electricity generation in 2050 as predicted by the DLR

The area required to generate the 4,800TWh of electricity for the EUMENA region in 2050 in the DLR's scenario would be: **27,745 or 44,444km^2** of land using Fresnels and parallel troughs respectively.

5.8.1 An estimate for sub-Saharan Africa

However as this thesis proposes is that much of this development is to take place in sub-Saharan Africa then that area should benefit in development terms, from this project too. Calculating the electricity requirement of sub-Saharan Africa accurately is beyond the scope of this thesis. However an estimate will be made based on parity development of sub-Saharan Africans and citizens of the MENA region. The *CSP-MED* report predicts that the electricity requirement of the MENA region will grow to 4100TWh yr^{-1} in 2050 and the population to just over 800million (Trieb et al., 2005b, p.71 and 74).

The median variant of the UN's world population prospects estimates that the population of Sub-Saharan Africa in 2050 will be 1,753,272,000 (United Nations, 2009). If the per capita electricity consumption in Sub-Saharan Africa were the same as in the MENA region then the electricity requirement of Sub-Saharan Africa would be nearly 9,000TWh of electricity yr^{-1} in 2050.

If this electricity were supplied by CSP the land requirement would be approximately **52,000 – 83,000km^2** using Fresnels and parallel troughs respectively. This sub-section has made many assumptions. For example it may be the Africa develops using decentralised photovoltaics, or that CSP units are distributed in areas throughout the drylands of other African nations. However, the estimate will be used in this thesis to help estimate how much land in the MENA deserts must be reserved for CSP units and hence cannot be irrigated in order to sequester carbon.

Additionally other infrastructure will need to be put in place such as RO plants and pipe-work that will further reduce the area of land available for vegetation. Furthermore some land will not be suitable for transformation for other reasons such as problems with terrain or the need for firebreaks. This will mean that the figures for carbon sequestration and consequently water requirements, electricity requirements and land requirements must all be revised. This will take place after estimates of other infrastructure requirements have been made in Chapter 6.

5.9 Summary

This chapter has shown that the use of CSP in the MENA deserts has the theoretical potential to provide many times the electricity required to provide the freshwater needed to irrigate the deserts. Additionally the deserts could provide the electricity required not only to meet the DLR's scenario for electricity use, but also to provide sub-Saharan Africa with electricity in 2050, based on parity with MENA citizens. Producing electricity from CSP is intended to reduce C emissions from fossil fuel consumption by mitigating the need to burn the fossil fuels that would have otherwise being used to produce that same amount of electricity. It is essential that the presence of an irrigated forest in the MENA deserts does not compromise that aim.

Theoretically CSP could be used to generate enough electricity to supply the citizens of the MENA region and sub-Saharan Africa with their electricity needs in 2050, export 700TWh yr^{-1} to Europe and desalinate enough fresh water from seawater to irrigate the MENA deserts.

5.9.1 Key data from Chapter 5

	Parallel troughs	Linear Fresnels
Land area required to produce electricity for desalination using CSP:	**712,509 – 793,259km^2.**	**444,803 – 495,214km^2**
Calculated from source data in: Trieb et al. (2009)		
Land area to set aside for other electricity production	**79,745km^2**	**127,444km^2**

Box 5.2 Key data from Chapter 5

Chapter 6 Revised calculations

6.1 Introduction

Chapter 6 will examine the area of the MENA deserts that may be available for solar-desalinated-irrigation-driven forestry based on factors such as area required for CSP units, RO plants and firebreaks. Then, based on this new area the estimates calculated throughout this thesis will be revised.

6.2 Land requirement

Chapter 5 estimated that to produce 75,256 - 84,811TWh yr^{-1} electricity using parallel troughs would require: **712,509 – 793,259km^2** of land using parallel trough CSP units and **444,803 – 495,214km^2** using linear Fresnels. This land would not then be available for growing forestry trees (though it would be possible to grow crops below linear Fresnels as mentioned in section 5.3.). Chapter 5 also estimated the land that would be required for CSP units in order to supply the MENA region and sub-Sub-Saharan Africa with electricity in 2050 and export 700TWh yr^{-1} to Europe. This amounted to 79,745km^2 or 127,444km^2 using linear Fresnels or Parallel troughs respectively.

So in total, up to 920,703km^2, or 8% of the 11,430,000km^2 of MENA deserts should be set-aside for electricity generation by CSP.

6.2.1 Firebreaks and other non-vegetated land

Evans and Turnbull (2004, p.380) suggest that in a tropical forest plantations about 20% of the land will be unplanted including land used for roads, and firebreaks and rocky areas. Although it is difficult to estimate the entire infrastructure that will be necessary to complete this project, there will be a requirement for large pipes to move the water. It will be assumed that this pipe-work will be included in the 20% of unplanted land, along with the roads. It may be possible that some of the CSP units could be located within this unplanted land. That however will not be assumed in this thesis, as further research is needed.

6.3 Land area available for forestry

This 20% reduction in the area that can be planted to forestry results in corresponding reductions in water and electricity requirements, and also carbon sequestration potential. Consequently a small amount of land that would have been used for CSP could now be used for forestry. However this increase in land will be small (~1%) compared to the estimated 20% of non-planted area in a forest (Evans and Turnbull, 2004, p.380), so will be discounted.

Area of MENA deserts: 11,430,000km^2.

Area for CSP units and RO plants MENA deserts: 929,276km^2 (920,703 + 8,573).

Area potentially available for forestry: 10,500,724km^2.

Area of forest non-planted: 2,100,145km^2 (20% of 10,500,724km^2).

Total potential planted area of MENA deserts: approximately **8.4 millionkm^2**.

This is 73.5% of the land area of the MENA deserts.

Box 6.1 Total area of the MENA deserts that could be planted with forestry

The calculation in Box 6.1 affects the previous calculations in this thesis as the land area for forestry is reduced to 73.5% of the value that they were based on. Consequently the calculations performed throughout this thesis, which must be revised.

6.4 Revised figures

Table 6.1 Summary of original values calculated throughout this thesis and new values based on a smaller land area.

<table>
<tr><th>Parameter</th><th>Original calculated value</th><th>New calculated value</th></tr>
<tr><td>Km^2 of MENA deserts</td><td>11.4million km^2 of MENA deserts</td><td>8.4million km^2 of MENA deserts</td></tr>
<tr><td colspan="3">Original estimate from Section: 1.2. Source data: Butterfield et al. (2003, p.1423 and 81)</td></tr>
<tr><td>C sequestration potential of <i>E. grandis</i> x <i>urophylla</i></td><td>8.7 – 16.2GtC yr^{-1}.</td><td>6.4 – 11.9GtC yr^{-1}.</td></tr>
<tr><td colspan="3">Original estimate from Section: 2.4.3. Calculated from source data in: Stape et al. (2004)</td></tr>
<tr><td>Water requirements of <i>E. grandis</i> x <i>urophylla</i></td><td>10,287 – 11,430 km^{3}yr^{-1}.</td><td>7,560 – 8,400 km^{3}yr^{-1}.</td></tr>
<tr><td colspan="3">Original estimate from Section: 2.8. Calculated from source data in: Stape et al. (2004)</td></tr>
<tr><td>Potential C difference after transformation of biome from desert to forest, with and without biochar.</td><td><table><tr><th>Veg^n (GtC)</th><th>Soil (GtC)</th><th>Total (GtC)</th></tr><tr><td>136</td><td>92 GtC</td><td>228</td></tr><tr><td>136</td><td>286 (194 in biochar)</td><td>421</td></tr></table></td><td><table><tr><th>Veg^n (GtC)</th><th>Soil (GtC)</th><th>Total (GtC)</th></tr><tr><td>100</td><td>68</td><td>168</td></tr><tr><td>100</td><td>210 (142 in biochar)</td><td>310</td></tr></table></td></tr>
<tr><td colspan="3">Original estimate from Section: 3.10.2. Calculated C in biomes from source data in: Watson et al. (2000, p.4) and biochar information in: Glaser et al. (2001).</td></tr>
<tr><td>C sequestration in top 20 cm soil during restoration.</td><td>3.3GtC yr^{-1} averaged over first 8 years.
2.2Gt yr^{-1} averaged over first 16 years.</td><td>2.4GtC yr^{-1} averaged over first 8 years.
1.6GtC yr^{-1} averaged over first 16 years.</td></tr>
<tr><td colspan="3">Original estimate from Section: 3.8.1. Calculated from source data in: Jia et al. (2005)</td></tr>
</table>

Parameter	Original calculated value	New calculated value
Electricity requirement to desalinate and move water	76,951 – 85,672TWh yr^{-1}. 10,089TWh yr^{-1} for the first 1,524km^3 water at 6.62kWh m^3 water. 66,862 – 75,583TWh yr^{-1} for the remaining 8,763 – 9,906km^3 yr^{-1} at 7.63kWh m^3.	56,144 – 62,553TWh yr^{-1}. 10,089TWh yr^{-1} for the first 1,524km^3 water at 6.62kWh m^3 water. 46,055 – 52,464TWh yr^{-1} for the remaining 6,036–6,876km^{3}yr^{-1} at 7.63kWh m^3.
Original estimate from Section: 4.6. Calculated from source data in: Trieb et al. (2007) with input from data in: Ornstein et al. (2009; Trieb et al. (2005b); Trieb et al. (2006); Hansen et al. (2007)		
Land area for RO	7,715 – 8,573km^2.	5,670 – 6,300km^2.
Original estimate from Section: 4.7. Calculated from source data in: Water-Technology (2010a) Based on the figures for the Ashkelon SWRO		
Land area required to produce electricity for desalination using CSP	Parallel troughs 712,509 – 793,259km^2. Linear Fresnels 444,803 – 495,214km^2.	Parallel troughs 519,852 – 579,194km^2. Linear Fresnels 324,532 – 361,578km^2.
Original estimate from Section: 5.7. Calculated from source data in: Trieb et al. (2009)		

6.5 Summary

Land area available for forestry: 8.4million km^2.

Annual C sequestration potential in *E. grandis* x *urophylla*: 6.4 – 11.9GtC yr^{-1}.

Annual C sequestration potential in top 20cm soil: 1.6 – 2.4GtC yr^{-1}.

Total annual C sequestration potential: 8 – 14.3GtC yr^{-1}.

The higher rate of C sequestration is 5.6GtC higher than current annual non-land-use-change anthropogenic emissions of 8.7GtC yr^{-1}.

Total C storage increase in SOC without the use of biochar (rate unknown): 68Gt.

Total C storage increase in SOC with the use of biochar (rate unknown): 210Gt.

Water required for irrigation: 7,560 – 8,400km^{3}yr^{-1}.

Electricity requirement for desalination and distribution: 56,144 – 62,553TWh yr^{-1}.

Area of parallel troughs needed to produce electricity for desalination: 519,852 – 579,194km^2.

Area of linear Fresnels needed to produce electricity for desalination: 324,532 – 361,578Km^2.

Chapter 7 Finances

Chapter 7 examines the costs, benefits and potential sources of income of a project to irrigate the MENA deserts. The current state of the carbon markets and the attempts by the Economics of Ecosystems and Biodiversity (TEEB) initiative to value ecosystem services are reviewed. Chapter 7 also looks at the possible value of any timber produced. The potential for farming below the linear Fresnel units is also considered.

7.1 Costs

7.1.1 Concentrating solar power (CSP) units

(Trieb et al., 2006, p.83) estimate the capital costs associated with installing the infrastructure to supply 700 TWh yr^{-1} electricity to Europe generated by CSP in the MENA deserts as requiring an investment of €395billion: €350billion for the CSP and €45billion for the High Voltage Direct Current (HVDC). At the time of writing the € and US$ were at parity (Trieb et al., 2006, p.61).

If there were a simple linear relationship between the cost of infrastructure to generate 700TWh yr^{-1} electricity and the cost of infrastructure to generate 56,144 – 62,553TWh yr^{-1} then the investment needed to desalinate and distribute the water to irrigate the MENA deserts would be approximately US$32 – 35trillion. However 56,144 – 62,553TWh yr^{-1} is approximately 80 times the amount of electricity on which the DLR have based their financial calculations. Therefore a linear relationship cannot be inferred and the cost cannot be predicted without substantial economic research beyond this thesis.

7.1.2 Desalination plants

The total capital costs of the Ashkelon SWRO desalination plant were US$212million. This desalinates 0.1km^3 water yr^{-1} (Water-Technology, 2010a). To irrigate the MENA deserts with 7,560 – 8,400km^3 water yr^{-1} would require the desalination capacity of the equivalent of 75,000 – 84,000 such plants. So, again, a linear relationship between the cost of the infrastructure to produce 0.1km^3 water yr^{-1} at Ashkelon and the cost of the water to desalinate the MENA deserts cannot be inferred and the cost cannot be predicted without further economic research.

7.1.3 CSP and Desalination

Alternative figures from the DLR (Trieb et al., 2007, p.48) for combined CSP desalination costs are based on a plant which cost €76.4million and desalinates 8,760,000m^3yr^{-1} costs. If the relationship between the cost and size of plant was linear this would equate to €8.72billion km^{-3} (or equal US$ at the time of writing (Trieb et al., 2007, p.10)) and to desalinate 7,560 – 8,400km^3yr^{-1} would require an investment of US$66 – 73trillion but again a linear relationship cannot be assumed and further economic research is necessary to estimate costs accurately.

Furthermore there has been some degree of double accounting within all of these figures. The Ashkelon plant has its own gas-generating boiler that is used to produce the electricity to power the RO process, which has already been accounted for in its price. The second set of figures given by the DLR also has some fossil-fuel backup availability included in the price, but these figures do not include the distribution costs of the freshwater. Without substantial further study many other costs may lie hidden.

Costs of CSP and RO cannot be estimated through simple linear extrapolation. However the costings for far smaller CSP and RO desalination plants serve to some degree to illustrate the heavy investment that would be necessary to set-up and run the plant capable of desalinating the volume of seawater required to irrigate the target regions of the MENA deserts in this proposal.

7.1.4 Pipework

It is difficult to estimate the other infrastructure necessary to complete this project, but there will be a requirement for large pipes to move the water. Ornstein et al. (2009) suggests that the costs of 'the irrigation systems … are probably a small percentage of the power costs.' But does not explain how this conclusion is reached. Stage I of the Great Manmade River (GMR) project in Libya required the laying of 1,200km of 4m diameter concrete pipe-work to move 0.002km^3 of fossil water from the aquifers below the Sahara desert to the coastal cities of Libya (Water-Technology, 2010b). The cost of this project was $14billion.

In order to irrigate the MENA deserts from coast to interior would require an undetermined amount of pipework. The Sahara desert stretches for over 4,800km east to west at its widest point (Mares et al., 1999, p.488), so to traverse the Sahara just once would require 4 times the length of pipework that was used in the GMR project. The desert may need to be traversed many times with large diameter pipework with possibly a further requirement for pipework of reducing diameters, certainly culminating in a drip irrigation system capable of delivering water to individual trees. This infrastructure would be needed for the Arabian Desert too. The exact quantities of pipework, the diameters of the pipes and the most efficient layout for delivering water to the trees will need to be calculated by hydro engineers and is out of the scope of this thesis.

7.2 Ecosystem Services

The millennium ecosystem assessment (MEA) (2005) was initiated in 2001 and coordinated by the UNEP. International institutions, governments, NGOs, business and indigenous people were present on its board as recognised stakeholders. Its purpose was to 'assess the consequences of ecosystem change for human well-being and to establish the scientific basis for actions needed to enhance the conservation and sustainable use of ecosystems and their contributions to human well-being' (MEA, 2005, p.ii).

Building on the MEA, The Economics of Ecosystems and Biodiversity (TEEB) (Sukhdev et al., 2010) is an international initiative to highlight the economic benefits of biodiversity and the costs of biodiversity loss and degradation. In 'Mainstreaming the Economics of Nature' (Sukhdev et al., 2010, p.8) report that halving deforestation rates by 2030 could prevent 0.41 to 0.74GtC yr^{-1} from entering the atmosphere and avoid damage due to climate change of more than US$3.7trillion in net present value terms. This thesis has estimated that the irrigated MENA deserts could sequester 8 – 14.3GtC yr^{-1}. The value that this sequestration would have in terms of avoiding damage due to climate change would need to be researched fully. The most basic assessment of the value of ecosystems is given in the document *Dead planet, living planet*, where it states that UNEP estimates that the essential services delivered by ecosystems are worth over US$72trillion yr^{-1}. (Nellermann and Corcoran, 2010). This exceeds the value of annual global GDP. Valuing ecosystem services is useful but as yet mechanisms do not exist whereby those services can be monetised.

Ecosystem services fall into main four categories: provisioning, regulating, supporting (habitat) and cultural (Sukhdev et al., 2010, p.33). Each category contains different services – see Appendix H. The services provided by a *Eucalyptus grandis x urophylla* forest in the irrigated MENA deserts would be primarily a regulatory service: Carbon sequestration and storage. However, it would also be a major supplier of raw materials – a provisioning service. One of these raw materials, timber, will be explored in section 7.3.3. Another potential raw material would be fuel wood. Table 7.1 shows that the medium class of *Eucalyptus grandis x urophylla* produces 3.3m^3 of timber ha^{-1}yr^{-1} in the branches alone. If some of this timber were exported to areas outside of the MENA desert after harvesting *Eucalyptus grandis x urophylla* stems as a building material it could reduce the amount of native forests that people need to cut for firewood, for example in the Sahel, and indirectly protect all four ecosystem services provided by those indigenous forests. Of course the timber in the branches cannot sequester carbon on a long timescale and be burnt as firewood too, but if the *Eucalyptus grandis x urophylla* mitigates the loss of natural forest then the sequestered carbon could be indirectly accounted for. Indeed the annual production of branch material alone, 2.8billion m^3 (calculated from medium class in Table 7.1) in the irrigated MENA deserts would exceed the 1.9billion m^3 of firewood consumed worldwide annually (FAO, 2010b).

A plantation of *Eucalyptus grandis x urophylla* will not provide the same wide range of ecosystem services as a diverse forest ecosystem, particularly in habitat and supporting services, but also in food provisioning. But it must be remembered that *Eucalyptus grandis x urophylla* is being used as a model in this thesis.

7.3 Income

7.3.1 Carbon sequestration

The cost of carbon capture and storage (CCS) for UK power stations in the East Midlands and Yorkshire reservoirs in the North Sea has been estimated as between £25 and £60t^{-1} of CO_2 (US$143 - 343t^{-1}C at £1=US$1.58) captured, transported and stored (Gough et al., 2006).

If the potential for the MENA deserts to sequester 8 – 14.3GtC yr^{-1} could be monetised at the cost of CCS – US$143 - 343t^{-1} – they have the potential to store the C equivalent of:

US$1 – 5trillion yr^{-1} or US$29 – 123trillion over twenty-five years.

These are substantial sums, but could they actually be realised through carbon trading?

7.3.2 Carbon trading

The European Union Emissions Trading Scheme (EU ETS) is the world's largest CO_2 emissions trading system, covering 11,000 power stations and industrial plants in 30 countries (Ellerman and Buchner, 2007). The price of carbon is not fixed and the European commission has ‘no view on what the price of allowances should be. The price is a function of supply and demand as in any other free market’ (European Commission, 2010). Data produced by Reuters carbon market company Point Carbon (2010) show that the price of carbon has always remained below €32t^{-1} (US$157t^{-1} C), with the price throughout 2009 less than half this figure – see Figure 7.1. So carbon usually trades on the open market at a value lower than the lower estimate for CCS.

Figure 7.1 Prices in the EU ETS, 2004 – present. Front year contracts for phase 1 and phase 2. NB this is the price for CO_2 not Carbon.

Source: Point Carbon (2010, p.3)

Currently only the EU plus three other European countries are signed up to EU ETS and the carbon market in 2009 was only $144billion (The World Bank, 2010). The price may be lower from the US after it implements its own scheme. Last year Bloomberg reported that a price floor of $10t^{-1} CO_2 ($37t^{-1}C) emitted would be set by US cap-and-trade legislation to start in 2012 (Lomax, 2009). So monetising the carbon sequestration potential of an irrigated MENA forest by carbon trading is limited at present. Furthermore it would need to complete with other carbon sequestration projects for the available carbon credits.

7.3.3 Timber

Fortunately, unlike CCS, forestry produces a useful product: timber. If used as a building material, timber can lock carbon away for many centuries, as witnessed by the presence of medieval timber-framed houses.

Table 2.2 *Eucalyptus grandis x urophylla* productivity and C sequestration showed annual amount of C the species sequestered. Table 7 shows this split into component parts and the volume of stem and branch material.

Table 7.1 Carbon sequestration of component parts of *Eucalyptus grandis x urophylla* and productivity in m^3 of stem and branch.

Class	Annual increase (t ha-1)	Foliage (t ha^{-1})	Branch (t ha^{-1})	Bark (t ha^{-1})	Stem (t ha^{-1})	Coarse Roots (t ha^{-1})	Stem (m^3 ha^{-1})	Branch (m^3 ha^{-1})
Low	15.8	0.5	1.3	1.4	9.3	3.2	18.6	2.8
Medium	20.4	0.6	1.2	1.6	13.0	3.9	26.1	3.3
High	29.3	0.9	1.8	2.0	20.2	4.4	40.4	4.1

Source: t ha^{-1} calculated from Stape (2002, p.169) using a 2:1 conversion for MAI to m^3 timber from Stape et al. (2010)

It can be seen from Table 7.1 that *Eucalyptus grandis x urophylla* produces 18.6 – 40.4m^3 stem material (logs) ha^{-1}yr^{-1}. The irrigated MENA deserts could produce 16 – 34 km^3 of logs yr^{-1}.

Eucalyptus logs traded wholesale for approximately US$150m^{-3} in December 2010 (Alibaba, 2010). If all 16 – 34km^3 of logs produced annually in the irrigated MENA deserts could sell at this price they would be worth US$2.4 – 4.8trillion yr^{-1} (US$60-120trillon over 25 years). This does not take into account inflation, but unfortunately nor does it account for market saturation being met and a crash in the price of timber. In 2009 the world produced 3.3billion m^3 of timber, of which 1.9billion m^3 was used as fuel and 1.4billion m^3 industrial roundwood (FAO, 2010b). The capacity of the irrigated MENA deserts to produce stem timber would exceed industrial roundwood consumption by 10 – 20 times.

7.3.4 Farms below CSP Fresnel

If Fresnel CSP units were adopted rather than parallel troughs, land would be available for farming beneath them (Trieb et al., 2007, pp.A-50-A62). Figure 5.4 shows an artists impression of horticulture below linear Fresnels. The land area below Fresnels would amount to 324,532 – 361,578km^2. This is an area larger than the entire UK (CIA 2010a). Moreover production beneath the Fresnels could concentrate on high value crops such as fruit and vegetables (Trieb et al., 2007, pp.A-50-A62). In 2008 the UK produced US$1.7billion of vegetables on 1,245km^2 and supplied the needs of 37million people (DEFRA 2010). The area of below the Fresnels is over 260 – 290 times larger than the UK vegetable growing land.

In order to farm below the Fresnels, more water would need to be desalinated. The quantity of water needed will need to be researched. Of course, land beneath Fresnels in the MENA deserts will have different growing conditions to land in the UK and the ideal species to grow will need to be further researched, but the potential is there both to generate income and to produce food for the MENA region and beyond.

Only the land beneath the CSP Fresnels used for desalination has been considered rather than including land for other electricity production.

7.3.5 Real Estate

One final item is to consider is the value of real estate in the transformed MENA deserts. There may come a time in the future when the world has transitioned away from fossil fuel use, e.g. through widespread adoption of CSP for electricity generation throughout other deserts of the world. At this time there may no longer be a need to regularly harvest fast-growing trees to remove carbon from the atmosphere. The irrigated MENA deserts could be gradually transition to more diverse ecosystems taking care to retain soil carbon. The infrastructure to supply the irrigation water will still be in place and some of the land could have value as real estate. Indeed, this infrastructure will enable a guaranteed water supply and the harvested *Eucalyptus* timber could be an abundant building material. To estimate the value of this real estate would involve too much speculation in this thesis, but should be considered as a future source of income.

7.4 Summary

This chapter has examined some of the costs, benefits and sources of income involved in a project to irrigate the MENA deserts.

Identified costs included CSP units, RO units and pipework. Capital costs could not be estimated as figures provided by the DLR for CSP costs and actual costs for the Ashkelon SWRO desalination plant for RO plants were for far smaller implementations and linear extrapolation of costs could not be assumed, but they do indicate that heavy investment will be needed in a project to irrigate the MENA deserts. Dedicated research is needed to estimate true capital costs, and operational costs. A further large capital cost is likely to come from supplying the pipework required to transport the desalinated water into the deserts. A full analysis of the layout and cost of this pipework will be required.

Benefits included climate change mitigation. The purpose of this thesis was to estimate the potential for reducing atmospheric CO_2 levels through solar-desalinated irrigated vegetation of the Sahara and Arabian deserts. In ecosystem services terms this is a regulating service. If preventing 0.41 to 0.74GtC yr^{-1} from entering the atmosphere can avoid damage due to climate change of more than US$3.7trillion over twenty years in net present value terms, then sequestering 8 – 14.3GtC yr^{-1} indicates a multi-trillion $US worth, but much more research is needed. Furthermore firewood produced as non-building-material in the forest could mitigate fuel use elsewhere.

Other sources of income include the value of the sustainably harvested timber itself, carbon credits and fruit and vegetables produced on farms below the Fresnels. Finally the land may have some future value as real estate. Valuing these potential income streams would be too speculative until further research is performed and this is the whole message of this chapter. A full cost benefit analysis of the whole project must be performed.

Chapter 8 Conclusions

8.1 Summary of the thesis

This thesis aimed to assess the potential for reducing atmospheric CO_2 levels through solar-desalinated irrigated vegetation of the Sahara and Arabian deserts through the review of existing literature. After reviewing carbon sequestration and water requirement data on several plant species it was decided to research the species of *Eucalyptus grandis x urophylla* in more detail because of the strength of the literature available about this forestry plantation tree. The thesis acknowledged the shortcomings of this tree and used it as a model rather than to recommend the establishment of an actual monoculture forest. The calculations performed throughout the thesis aimed to provide an early indication of whether existing technologies such as concentrating solar power and reverse osmosis were feasible for the irrigation of the sites and establishing vegetation. The thesis focussed on the science and technology rather than on the emergent sociological and geopolitical issues associated with a study of this nature.

This thesis proposed that 73.5% of the 11,430,000km^2 of land that currently makes up the MENA deserts (8.4 millionkm^2) could be transformed into forests by irrigation using water produced by desalinating seawater, using electricity produced by concentrating solar power. The MENA deserts could host a forest of *Eucalyptus grandis x urophylla* capable of sequestering 6.4 – 11.9GtC yr^{-1}. Additionally the soil across this area may sequester C at the rate of 1.6 – 2.4GtC yr^{-1} in top the 20cm soil, with potentially more in the deeper soil profile. In total, the results indicated that the proposed forest could sequester approximately 8 – 14.3GtC yr^{-1} in the vegetation and upper profile of the soil. Non-land-use-change anthropogenic emissions of carbon currently stand at 8.7Gt yr^{-1}. The higher estimate of C sequestration is 5.6GtC yr^{-1} greater than emissions.

The total increase in organic carbon in the top 30cm of soil after transformation from desert to forest ecosystem could be 68Gt through natural soil-building processes. If biochar was included at a rate that raised the total SOC to 250t ha^{-1} the transformed deserts could hold 210GtC, but the preparation of this biochar from biomass would release at least half of the sequestered carbon.

The forest would have a water requirement of 7,560 – 8,400km^3 yr^{-1}, which would be provided by desalinating seawater. Most would be desalinated using reverse osmosis in plants covering approximately 5,670 – 6,300km^2 of land. These RO plants would require electricity and additional electricity would be needed to pump the water across the deserts. The total electrical requirement would be 56,144 – 62,553TWh yr^{-1}. This thesis proposes that this electricity could be produced using concentrating solar power units. These units would cover 324,532 – 361,578km^2 of land in the case of linear Fresnels, or 519,852 – 579,194km^2 in the case of parallel troughs.

The costs, benefits and potential sources of income of a project to irrigate the MENA deserts were investigated. Major costs identified involved the installation of the infrastructure (CSP units, RO plants and irrigation pipework). Benefits of the forest in terms of directly supplied ecosystem services were regulating and provisioning services, and indirectly all four services, provisioning, regulating, habitat and cultural if branches of *Eucalyptus grandis x urophylla* timber replaced firewood from indigenous trees outside of the project area. Potential income streams included carbon trading, timber, farming of vegetables below the Fresnels and possible sale of land as real estate. Monetary estimates of costs and income were beyond the scope of this thesis.

8.2 Limitations of the thesis research

This thesis relied on pre-existing research findings. This data, particularly regarding vegetation and soil was correlated from different projects and regions of the world and combining it brought limitations in terms of applicability. Furthermore certain data such as the transpiration efficiency and the carbon sequestration potential of a range of tree species was not known. Ideally a forest would consist of a wide diversity of species within multiple layers as it is well known that a biodiverse ecosystem is more resilient to environmental change and less prone to degradation and this is true both above and below ground biota (Wittebolle et al., 2009), but in order to carry out the calculations within this thesis the remit had to be simplified. The thesis therefore concentrated on the high-yielding tropical-forestry-plantation tree *Eucalyptus grandis x urophylla* as the data was available for this species. Data was not available on the water requirements of different tree species, with different soil types and differing water vapour pressure and under differing irrigation regimes. Neither was there data available concerning the nutritional requirements of the vegetation and how that may affect carbon sequestration rates and transpiration efficiency. The thesis relied on data from forests in Brazil and used this to model growth rates of a theoretical forest in the MENA deserts. The effects on evapotranspiration and water requirements due to differences in RH and the effects for wind were not modeled. Ideally ecosystems, such as multi-layered forests or even forest gardens should be modeled rather than individual species.

Data on SOC increase under desert restoration projects was also limited and the data that was available was limited in scope to the top layers of the soil profile. Data was not available on the SOC build up during the vegetation of hyper-arid land, but rather land that had undergone relatively recent desertification. Most of the data regarding the potential of soils to sequester carbon was broad in scope. The true extent of each soil type of the MENA region was not measured so the actual land that could be planted was estimated. Although highly efficient drip irrigation was discussed this thesis was limited in its investigation of aspects of establishing the forest beyond irrigating it such as the high water drainage down soil profile owing to the sandy soil.

For the purposes of this thesis, the nutrient content of the MENA deserts (potassium, phosphate and trace elements) was assumed to be similar to the Congo of Amazon basin, based on research by Ornstein et al (2009). This assumption is a limitation of the thesis that will require research to verify.

With regard to electricity production and desalination, this thesis relied heavily on data supplied by the DLR (Trieb et al., 2005b; Trieb et al., 2006; Trieb et al., 2007; Trieb et al., 2009). In Africa this data was restricted to the five northernmost countries, Morocco, Algeria, Tunisia, Libya and Egypt. The electricity producing potential of other Saharan and Sub-Saharan African countries was not assessed, the countries' future electricity demand and any future freshwater deficit were not modeled.

The irrigation of 8.4 million km^2 of desert land with 7,560 – 8,400 km^3 water yr^{-1} may have profound effects on the climate of the MENA region and beyond. Almost all of the water supplied as irrigation would be evapotranspired into the atmosphere. The IPCC (2007b) state that 'water vapour is the most important greenhouse gas'. The effects that this increase in water vapour would have locally, regionally and globally was not investigated. Furthermore this additional water vapour may affect the actual amount of DNI that reaches the CSP units. This too must be modelled.

This thesis took an industry standard figure of 4.2kWh m^{-3} for the electricity required to desalinate seawater by RO. However, a major factor affecting the efficiency of RO is the salinity of the feed seawater. The exact locations of the desalination plants were not known and hence the salinity of the incoming seawater was also unknown. Furthermore the effect of the return of hyper saline brine to the ocean from the RO plants is an environmental concern that was not considered in the thesis. Another unmeasured environmental issue was the embodied energy of the infrastructure involved in the desalination and distribution of the water. In particular the amount of concrete that might be needed to form the pipework to move the water around was unknown.

This thesis focused on scientific issues rather than sociological and geopolitical issues. It did not consider land tenure issues. Both the Arabian and the Sahara desert span several sovereign states, inhabited by people of different cultures, religions and belief systems. The willingness of the individual governments to participate in a scheme to transform some, or most, of the land within the borders of their nation into an irrigated forest would need to be explored. The ownership and land access rights of individuals or groups, such as the Bedouin and Tuareg would also need to be researched. The Sahara stretches across two politically diverse entities, northern ‘Arab’ and sub-Saharan ‘black’ Africa. The African nations included in the Desertec initiative are all members of the Union for the Mediterranean (with the exception of Libya who has observer status) and are relatively economically advanced compared to the southern states. There are also major differences in the level of development in nations in the Arabian Peninsula. Trans-border issues include possible conflict between countries, for example Morocco’s continual territorial claim to Western Sahara, which is refuted by the rest of the African Union. This has lead Morocco to self-exclude from the African Union, the only nation to do so, while Western Sahara is a recognised sovereign state within that grouping. The future electricity requirements of sub-Saharan Africa were briefly discussed but not modeled. Neither were future water requirements of sub-Saharan.

The dynamics of the carbon cycle need to be modelled. The thesis estimated that the forest could sequester 8 – 14.3 GtC yr^{-1} in the vegetation and upper profile of the soil. Even if that carbon was locked away indefinitely, it does not mean that the level of atmospheric carbon would be reduced by the same amount. If more carbon is sequestered in the MENA region than is released by non-land-use-change anthropogenic emissions, there may be unforeseen effluxes from soils or the oceans to the atmosphere.

This thesis researched the carbon sequestration potential of a forest established in the MENA deserts with the necessary infrastructure to provide the water for irrigation in place. In reality such a project would take many years to realise. This thesis has not attempted to model this project in time, where the project may begin, and how long it would take to complete. Similarly, the annual water requirements and growth rates of *Eucalyptus grandis* x *urophylla* were averaged from plantations that ranged from 5.1 – 7.9 years old (Stape et al., 2004). Younger trees would require less water and sequester less carbon. This has not been modelled.

Chapter 7 - Finances - was limited to a high level discussion. Actual costings were beyond the scope of this thesis.

Due to the nature of the research, and despite the literature review, the breath of this topic means that issues will have been overlooked. These issues may arise as practical studies are performed. In terms of the success of this project political will must be obtained and land tenure issues resolved in advance of a large-scale implementation. Small-scale trials can begin once suitable locations have been found, funding secured and permission obtained.

8.3 Implications of the case made for existing orthodoxy

Climate change mitigation proposals often focus on reducing GHG emissions. Indeed that is central to the Desertec Foundation's proposals. This thesis does not argue against this viewpoint. However, preventing carbon emissions does not sequester carbon that has already been emitted. The IPCC (2007a) defines climate change mitigation as 'An anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases'. This thesis focussed on the latter.

Some observers may criticise the establishment of a forest across the MENA deserts as a form of geoengineering. Indeed large-scale forestation has been explicitly cited as such (PPIGW et al., 1992, p.433). However, the release of 500GtC of fossil carbon from the geological cycle into the atmosphere as CO_2 since the beginning of the industrial revolution, and continues to be released today is also geoengineering. This thesis does not propose the type of geoengineering that attempts to 'work-around' the atmospheric CO_2 problem through the use of, for example, sun-shields, that attempt to tackle temperature rise and do not help crises such as ocean acidification (Hansen, 2009, p.230), but proposes a land use change, photosynthesis-based form of geoengineering to move C from the atmosphere into the terrestrial sinks.

Atmospheric CO_2 is now regarded as a dangerous pollutant by some authorities, including the US EPA (2009). However, atmospheric CO_2 is, in fact, an essential feedstock for tissue creation via photosynthesis by terrestrial primary producers and ultimately all life forms that depend on green plants, including humans. This thesis has viewed the problem as an imbalance in the global carbon cycle rather than a problem due to CO_2 itself. Furthermore the thesis has considered the potential of carbon as a resource. Carbon capture and storage initiatives view CO_2 as a harmful by-product of fossil fuel consumption that must be locked away at expense. This thesis has viewed CO_2 as the raw material for producing large quantities of useful timber, which could ease the logging pressure of old-growth natural forest ecosystems in the future, and to transform the desert sands into soils rich in SOC.

Irrigation is now carried out on a land area of about a third that proposed in this thesis (FAO, 2010). Extraction often exceeds replenishment and past societies, including famously the Maya, who depended on irrigation have collapsed after droughts failed to replenish the catchment areas their irrigation channels depended on (Diamond, 2006, pp.157-177). This thesis proposes that in irrigating the MENA deserts people can take control of the fresh-water supply. Table 4.1 shows that seawater is many times more abundant on planet earth than freshwater. This thesis has shown this it can be sustainably desalinated and used to grow vegetation. An irrigation system spanning the MENA deserts would be robust in the face of climate change, as it would put people in control of the freshwater supply instead of relying on the hydrological cycle. It would be a form of climate change adaptation as well as mitigation, because human beings would control the availability and flow of water, as long as the CSP units functioned.

A megaproject is a multi-billion (US$) project (Flyvbjerg et al., 2003, p.1). A project to irrigate the MENA deserts would be a multi-trillion (US$) project. However the damage due to climate change could exceed the costs of this project by many times. Small efforts to reduce the impacts of climate change, often only achieve small results (MacKay, 2009, p.3). This project would require a large investment, but could be worth US$multi-trillon yr^{-1} in terms of averting dangerous climate change. Additionally there would be some return on investment in purely economic terms, but this would need to be fully researched.

8.4 Implications in terms of future research required

This thesis has been a theoretical overview of the potential for irrigated forests to sequester carbon in the MENA region. Practical trials are essential to test all aspects of this research. In the case of the biological experiments on a field scale, large replicated split-plot trials should be conducted.

8.4.1 Vegetation and soil

There must be a serious research effort into the carbon sequestration potential of plant species, particularly woody species, other than the ones mentioned in this thesis (*Ananas comosus*, *Bambusa bambos*, *Eucalyptus grandis x urophylla*). This needs to be related to the transpiration efficiency of these species and trials will need to be performed to ascertain that too. All of the African trees in Table D1 would need to assessed in this manner. Researching *Eucalyptus grandis x urophylla*, (Stape et al., 2004) ascertained that the most productive sites used water most efficiently. The irrigation would need to be varied in trials within tree species to ascertain the optimum level of irrigation for maximum carbon sequestration and water use. Other variables to test would be different nutrient levels, soil types, methods of irrigation, the application of mulch, presence of nitrogen fixing bacteria and species of mycorrhizae present or introduced. The existing nutrient levels of the MENA deserts would need to be researched on an area-by-area basis and any deficiencies addressed. With respect to methods of irrigation, the establishment of a forest on the sand of the MENA deserts in respect to aspects such as rate of water flow down the soil profile requires more research.

Bambusa bambos was seen to have a maximum aboveground carbon sequestration rate of 23.9 tC $ha^{-1}yr^{-1}$, which is higher than *Eucalyptus grandis x urophylla* and bamboo in general does have some advantages over wood as a building material (Janssen, 1995, pp.2-3). However this species could not be used in this thesis, as the transpiration efficiency was not known. This should be researched. This thesis briefly touched on the use of biochar to build SOC. Non-woody species with very high water use efficiency and high growth rates such as *Ananas comosus* may have a role to play in improving soils if pyrolysed. Indeed if the transpiration efficiency is sufficient, there may be potential to pyrolyse bamboo also. Trials involving biochar in desert soils, including interactions with mycorrhiza, influence on water holding and nutrient availability and affect on SOC need to be researched. Combinations of plant species should be trialed in groupings to research the potential for synergies in water use and carbon sequestration, and the most fitting species to use in a succession to build SOC should be studied. This should lead eventually to entire forest ecosystems being established and studied.

For each vegetation trial that takes place, the effect on levels of both SOC and SIC should be studied. This research should look at the deeper layers of the soil profile, rather than be restricted to the top 20 or 30cm. Section 3.4 showed how soil respiration rates vary between and within different established ecosystems. The actual soil respiration rate would need to be measured for an ecosystem in transition from desert to forest at regular intervals during the process. The rate of soil building is a major research area.

8.4.2 Infrastructure

This thesis estimated the electricity that could be generated in the MENA region and land area required for parallel trough and linear Fresnel CSP. This used average figures for DNI and LUE. An area-by-area assessment of countries in the MENA region and beyond must be made to assess the potential of individual sites in terms of electricity producing capacity. Similarly an assessment of suitable areas for RO desalination plants should be made. Furthermore the consequences that the water vapour transpired by the vegetation in an established forest may affect the DNI and would need to be modelled.

The amount of pipe-work required to irrigate the deserts and the most efficient layout for moving the water around needs researching. Also the most efficient places to site CSP pumping stations to minimise losses due to moving electricity should be studied. The infrastructure will contain embodied energy. Ways to minimise this should be sort and the actual availability of the raw materials and labour force guaranteed.

8.4.3 Geopolitical

The DLR study focussed on assessing the coastal and economic CSP potential of nations in the MENA region. There must be substantial investigations performed into geopolitical and sociological factors that exist within and between the nations involved. Furthermore, the potential of other African nations, with land within the Sahara desert, such as Western Sahara, Chad, Mali, Mauritania, Niger and Sudan should also be assessed, both in technical and again, geopolitical terms. Additionally Sahelian nations with coastal potential such as Senegal and Eritrea should be similarly studied. This thesis assumed that there would be 8.4million km^2 of MENA deserts available for irrigation. A thorough assessment of the suitability of all of the land within the MENA deserts should be made. This should include all aspects of land tenure within states and cross-border and co-operation between states.

8.4.4 Financial

The finances section of this thesis discussed costs, benefits and income streams at a general level. A thorough study must be made regarding the finances of this project. Specifically actual cost estimates should be made for the infrastructure, taking into account economies of scale and operational as well as capital costs. A full ecosystem services assessment should be performed comparing a desert, a *Eucalyptus grandis* x *urophylla* forest, and a multi-layered biodiverse forest. The potential income streams from carbon credits, timber, farm produce and produce from food forests should also be thoroughly researched.

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Appendices

Appendix A Notes regarding units used in the thesis

SI units as defined by the BIPM (2006) are used throughout this thesis.

Numbers

1 billion = 10^9 (1000 million)

1 trillion = 10^{12} (million million)

Mass

The SI base unit of mass is the kilogram (10^3 g). Derived units include the megagram (10^6 g) and petagram (10^{15} g). One megagram is equal to one tonne. While the tonne is not an SI unit, it is accepted for use with the system. The use of the unit tonne and the derivatives is more widespread than the use of the corresponding units based on the kg.

Table 8.1 Summary of units of mass used in this thesis and their relationship to each other.

Units used in thesis	Multiplier	Corresponding (SI) unit	
kilogram	10^3g	kilogram	10^3g
tonne (t)	10^3kg	megagram (Mg)	10^6g
kilotonne (kt)	10^3t	gigagram (Gg)	10^9g
megatonne (Mt)	10^6t	teragram (Tg)	10^{12}g
gigatonne (Gt)	10^9t	petagram (Pg)	10^{15}g

Source: BIPM (2006)

Length, area and volume

The SI unit of length is the metre. A widely used derivation is the kilometre (10^3m).

This thesis refers to units of area and volume based on the metre.

When discussing water use the units cubic metre (m^3) and cubic kilometre (km^3) are used. When discussing land area ha and km^2 are used.

Table 8.2 Summary of units of length, area and volume used in this thesis and their relationship to each other.

Length	Multiplier	Area	Multiplier	Volume	Multiplier
millimetre (mm)	10^{-3} m				
				litre (l)	10^{-3} m^3
metre (m)		square metres (m^2)		cubic metres (m^3)	
		hectare (ha)	10^4 m^2 or 10^{-2} km^2		
kilometre (km)	10^3 m	square kilometres (km^2)	10^6 m^2	cubic kilometres (km^3)	10^9 m^3

Source: BIPM (2006)

Rainfall is often expressed in one-dimensional units. To obtain volume one must define an area. One square metre is convenient. For example an annual rainfall of 600mm is equivalent to a volume of $0.6m^3$ falling on $1m^2$ land a year.

Energy and power

This thesis refers to the units kilowatt-hour (kWh) and the larger gigawatt-hour (GWh) and terawatt-hour (TWh). These are units of **energy**. The thesis also refers to these units per unit time (i.e. the rate). For example terawatt-hour yr^{-1} when referring to the power used by society and required to desalinate seawater. These are units of **power**. They are ultimately derived from the SI units metre, kilogram and second.

The BIPM (2006, p.144) describe the watt as ‘the power which in one second gives rise to energy of 1 joule’. The units are J s-1, or derived from SI units, m^2 kg s^{-3}.

Table 8.3 Summary of units of energy and power used in this thesis and their relationship to each other.

Energy	Multiplier	Power	Multiplier
Watt-hour (Wh)		Watt-hour $year^{-1}$ (Wh yr^{-1})	
kilowatt-hour (kWh)	10^3 Wh	kilowatt-hour $year^{-1}$ (kWh)	10^3 Wh yr^{-1}
megawatt-hour (MWh)	10^6 Wh	megawatt-hour $year^{-1}$ (MWh)	10^6 Wh yr^{-1}
gigawatt-hour (GWh)	10^9 Wh	gigawatt-hour $year^{-1}$ (GWh)	10^9 Wh yr^{-1}
terawatt-hour (TWh)	10^{12} Wh	terawatt-hour $year^{-1}$ (TWh)	10^{12} Wh yr^{-1}

Source: BIPM (2006)

Carbon

When estimating emissions and sequestration of CO_2 throughout this thesis the mass of carbon is used rather than CO_2. This leads to consistency with the scientific literature and facilitates easier calculation with regard to timber and soil sequestration.

The molecular weight of CO_2 is 44 g mol^{-1}. This consists of one carbon atom of atomic weight 12 and two oxygen atoms of atomic weight 16 each.

One tonne of CO_2 contains 0.273 (12/44) tonnes of carbon and conversely one tonne of carbon contains the equivalent of 3.67 (44/12) tonnes of CO_2.

Appendix B Summary of sources of data

Table B1 summarises the robustness of the major sources of data used in this thesis, including, where appropriate the journal impact factor and article citations. Most of these are the data that contributed directly to the calculations in this thesis.

Table B.1 Robustness of major sources of data used in this thesis.

Author(s)	Study(s)	Publication and data quality	Comments
Chapter 2 – Vegetation			
Stape et al. (2004)	Eucalyptus production and the supply, use and efficiency of use of water, light and nitrogen across a geographic gradient in Brazil.	Forest Ecology and Management Journal Impact factor: 1.95. Article Citations: 59. Robust data.	Supplied most of the information for section 2.4.3 *E. grandis x urophylla.* Used to calculate carbon sequestration and transpiration efficiency.
United States Department of Energy. (No date)	Quick-reference list of conversion factors used by the Bioenergy Feedstock Development Programs at Oak Ridge National Laboratory.	Bioenergy Feedstock Information Network Reasonable estimate. Used by US Department of Energy.	Used to calculate carbon content of *E. grandis x urophylla* biomass
Howell, (2001)	Enhancing Water Use Efficiency in Irrigated Agriculture	Agronomy Journal Journal Impact Factor: 1.416 Article Citations 138 Robust article.	Used to assist estimating the water requirements of *E. grandis x urophylla* under irrigation 2.8. Not directly involved in any calculation
Bainbridge (2001)	Buried clay pot irrigation: a little known but very efficient traditional method of irrigation	Agricultural water management Journal Impact factor: 2.016 Article Citations: 10 Good article.	As above.

Author(s)	Study(s)	Publication and data quality	Comments
Bainbridge (2007)	A guide for desert and dryland restoration: new hope for arid lands	Book Written by experienced university professor. Robust data.	Book collates original research findings and material from peer-reviewed journals. As above.
Ornstein et al. (2009)	Irrigated afforestation of the Sahara and Australian Outback to end global warming.	Climatic change Journal Impact Factor: 3.635 Citations: 7 Broad statement without supporting reference that will need verifying.	Statement regarding nutrient availability in deserts being comparable to rainforests.
Chapter 3 – Soil Carbon			
Luo and Zhou (2006)	Soil Respiration and the Environment	Book Written by experienced researchers Robust.	Collates information from peer-reviewed soil respiration rate studies. Used for background research. Not directly used in any calculations.
Watson et al. (2000)	Land use, land-use change and forestry A Special Report of the Intergovernmental Panel on Climate Change	IPCC special report Citations (Google Scholar referring to Google books version): 392 The authors state 'There is a considerable uncertainty in the numbers given because of ambiguity of definitions of biomes' (Robert T. Watson et al., 2000, p.4).	Soil carbon of various ecosystems down to a depth of 1 metre Table 3.1. Used to calculate extra SOC that could be stored converting desert to forest.

Author(s)	Study(s)	Publication and data quality	Comments
Glaser et al. (2001)	The 'Terra Preta' phenomenon: a model for sustainable agriculture in the humid tropics.	Naturwissenschaften Journal Impact Factor: 2.316 Citations: 179 Robust data.	Supplied estimate the tropical soils could contain up to 250 tC ha^{-1} due to presence of biochar. Table 3.10 Used to calculate extra SOC that could be stored converting desert to forest with the addition of biochar.
Lehmann et al. (2006)	Bio-char sequestration in terrestrial ecosystems–a review.	Mitigation and Adaptation Strategies for Global Change Journal Impact Factor: Unknown Citations: 173 Rough estimate.	Used to estimate that 50% of C in pyrolysed material will be lost.
Jia et al. (2005)	Microbial biomass and nutrients in soil at the different stages of secondary forest succession in Ziwulin, northwest China.	Forest Ecology and Management Impact factor of Journal 1.95. Most cited forestry journal. Article cited by 39. Robust data.	Used to estimate the amount of SOC build up under secondary forest succession in section 3.8.1 – extrapolated to forests in the MENA deserts.
Chapter 4 – Desalination			
Trieb et al. (2007)	Concentrating solar power for seawater desalination.	DLR report commissioned by Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Germany Robust government report. Industry standard figure for RO.	Provided average figure for RO electrical requirement of 4.2 kWh m^{-3}. Used to calculate electrical requirements to desalinate the water to irrigate the MENA region.

Author(s)	Study(s)	Publication and data quality	Comments
Tahri (2001)	The prospects of fresh water supply for Tan Tan City from non-conventional water resources.	Desalination Journal Impact Factor: 2.034 Citations: 5 Reasonable.	Verifies average figure for RO electrical requirement of 4.2 kWh m^{-3}.
Ornstein et al. (2009)	Irrigated afforestation of the Sahara and Australian Outback to end global warming.	Climatic change Journal Impact Factor: 3.635 Citations: 7 Reasonable estimate.	Estimate of electrical requirement to pump water across the Sahara. Used to calculate electrical requirements to move the desalinated water.
Hansen et al. (2007)	Imaging ruptured lithosphere beneath the Red Sea and Arabian Peninsula.	Earth and Planetary Science Letters Journal Impact Factor: 4.062 Citations: 18 Reasonable estimate of elevation of Arabian peninsula. Elevation of Arabian desert will need more study.	Cited the average elevation of the Arabian peninsula as being around 1,000 m. Used in conjunction with Ornstein's calculations to estimate the electrical requirements to move the desalinated water.
Trieb et al. (2006)	Trans-Mediterranean interconnection for concentrating solar power.	DLR report commissioned by Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Germany. Robust government report. Data used to make a rough estimate made in thesis.	Used to estimate electrical losses due to transmitted electricity over HVDC cables.

Author(s)	Study(s)	Publication and data quality	Comments
Trieb et al. (2005)	Concentrating solar power for the Mediterranean region	DLR report commissioned by Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Germany. Robust government report.	Desalination requirement and energy use of the MENA region in 2050. Used to estimate water to be supplied to MENA region in addition to desalination for irrigation. Also provided coastal potential which allowed the calculation of how much desalination could take place with less energy.
(Water-Technology, 2010a)	Ashkelon Seawater Reverse Osmosis (SWRO)	Website for the wastewater industry. Commercially supplied data. Simplistic extrapolation in thesis.	Provided land area km^{-3} water desalinated requirement of RO plant. Used to estimate land area requirements for MENA deserts section 4.7. Also supplied RO electrical figure of 4 kWh m^{-3} (Not used but helps validates figure of 4.2 that is used).
Chapter 5 – Electricity generation by concentrating solar power			
Trieb et al. (2005)	Concentrating solar power for the Mediterranean region	DLR report commissioned by Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Germany Robust government report.	Technical, Economic and Coastal potential of countries in the MENA region Table 5.4

Author(s)	Study(s)	Publication and data quality	Comments
Trieb et al. (2009)	Global potential of concentrating solar power.	DLR. Conference paper Robust within a range of values.	World Direct Normal Irradiation and Land Use Efficiency of CSP units. Used to calculate land requirement for CSP for desalination.
Mackay (2009)	Sustainable Energy – without the hot air	Book Robust. Respected author.	World energy use in 2050 if everyone consumed like a European. Use in conjunction with the row above to ascertain how much of the MENA deserts to set-aside for potential future CSP electricity generation.
Chapter 6 – Revised calculations			
Evans and Turnbull (2004)	Plantation forestry in the tropics	Book Citations: 46. Broad estimate.	Used to estimate that 20% of plantation land is unplanted in section 6.2.1.
Chapter 7 – Finances			
Trieb et al. (2006)	Trans-Mediterranean interconnection for concentrating solar power.	DLR report commissioned by Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Germany Predictive estimate.	Used to estimate electricity producing infrastructure (CSP and HVDC) costs.

Author(s)	Study(s)	Publication and data quality	Comments
water-technology.net	Ashkelon Seawater Reverse Osmosis (SWRO)	Website for the wastewater industry. Commercially supplied data. Simplistic extrapolation in thesis. Weak prediction.	Used to estimate cost of desalination by RO.
water-technology.net	GMR (Great Man-made River) Water Supply Project, Libya	Website for the wastewater industry. Commercially supplied data. Very speculative.	Used to estimate cost of pipework.
Sukdev et al. (2010)	TEEB is an international initiative to highlight the economic benefits of biodiversity and the costs of biodiversity loss and degradation	Wide range of values. Speculative.	Used to estimate potential value of MENA deserts as a carbon sink.
Stape. (2002)	Production ecology of clonal Eucalyptus plantations in north-eastern Brazil.	Colorado State University. Strong data. Most material in thesis published as ‘Eucalyptus production and the supply, use and efficiency of use of water, light and nitrogen across a geographic gradient in Brazil.’	PHD thesis. Used to calculated the split of *E. grandis x urophylla* timber into component parts in Table 7.1

Author(s)	Study(s)	Publication and data quality	Comments
Stape et al. (2010)	The Brazil Eucalyptus Potential Productivity Project: Influence of water, nutrients and stand uniformity on wood production.	Forest Ecology and Management Impact factor of Journal 1.95. Most cited forestry journal. Article cited by 1. Robust publication and data.	Used to calculated the m^3 of *E. grandis x urophylla* timber in Table 7.1
Point Carbon (2010)	Carbon 2010 - Return of the sovereign	Company report Annual Survey – Speculative.	Used to estimate price $tonne^{-1}$ of sequestered carbon via carbon trading
The World Bank (2010)	Carbon Finance - State and Trends of the Carbon Market Report 2010	World bank Report	Used to estimate potential value of sequestered carbon via carbon trading
alibaba.com (2011)	Not applicable.	Global trade website. Robust data as real prices. However very speculative that the price will be the same in 25 years or that a market will exist for the volume of timber available.	Use to estimate value of timber
DEFRA (2010)	Basic Horticultural Statistics	UK government farming data. Robust for UK yield ha^{-1} and price received. Speculative in thesis for yield below Fresnels.	Used to estimate yield and price of fruit and vegetables grown below Fresnels based on UK farm prices.

Source: Reuters (2011) for Journal impact factors. Google Scholar (2011) for number of citations.

Appendix C   Visualising the problem.

This thesis investigates the sequestration of atmospheric carbon in terrestrial ecosystems including forests. If the forest trees were harvested and the captured carbon was stored as timber, how large would a stack be? For illustrative purposes consider dry *Eucalyptus* timber with a weight (t): volume (m^3) ratio of 0.5 (Stape et al., 2010) and a carbon content of 50% (BFINetwork, n.d.). This will contain 0.25 t C m^3.

Annual emissions

In order to store the estimated 8.7 Gt of carbon emitted through non-land-use-change anthropogenic activities in 2008 (Le Quéré et al., 2009), 17.4 billion tonnes or 34.8 billion m^3 of air-dried timber would be required to be sustainably harvested and permanently stored. This is 34.8 cubic kilometres of wood. To put this into context, consider the Great Pyramid of Giza. This structure was originally 0.1466 km tall on a square base of side length 0.2304 km (Herz-Fischler, 2000, p.11). If it were a solid mass, the volume would be 0.0026 km^3. To store the volume of carbon emitted into the atmosphere every year as air-dried timber would require a pyramid with 13,415 times the volume of the Great Pyramid of Giza. This timber pyramid would cover 30km^2 and stand 5.47 km high - 7.86 times the height of the Empire State Building (R. Miller, 2010).

Historic emissions

Since industrialisation non-land-use-change anthropogenic activities have emitted 500 Gt of carbon (Allen et al., 2009, p.1163). In order to draw this out the atmosphere would require 2000 km^3 of timber, equivalent to 770,996 the volume of the Great Pyramid of Giza. This pyramid would stand 13.44 km high: one and a half times height of Mount Everest (8.848 km (CIA, 2010c)). To draw out the 233.2 Gt of carbon that have remained in the atmosphere would require a pyramid of timber 10.42 km high.

Back to 350 ppm

In order to get atmospheric CO_2 levels back down to 350ppm would require removing 84.8 Gt of carbon from the atmosphere would require 339.2 km3 of timber, equivalent to 130,761 the volume of the Great Pyramid of Giza. This would stand 7.44km high: 84% the height of Mount Everest.

Table C.1 Volume of timber as pyramids of timber to illustrate the size of the task

Pyramid and Number	Mass (GtC)	Volume (km^3 timber)	Height (km)	Area (km^2)	Volume Equivalent to Great Pyramid of Giza
The Great Pyramid of Giza (1)	0.0006	0.0026	0.14	0.05	1
Annual Emissions (2)	8.7	34.8	3.48	29.97	13,415
Get down to 350 ppm (3)	84.8	339.2	7.44	136.76	130,761

Emissions since industrialisation that have remained in the Atmosphere (4).	233.2	932.8	10.42	268.43	359,593
Emissions since industrialisation (5)	500	2000	13.44	446.34	770,996

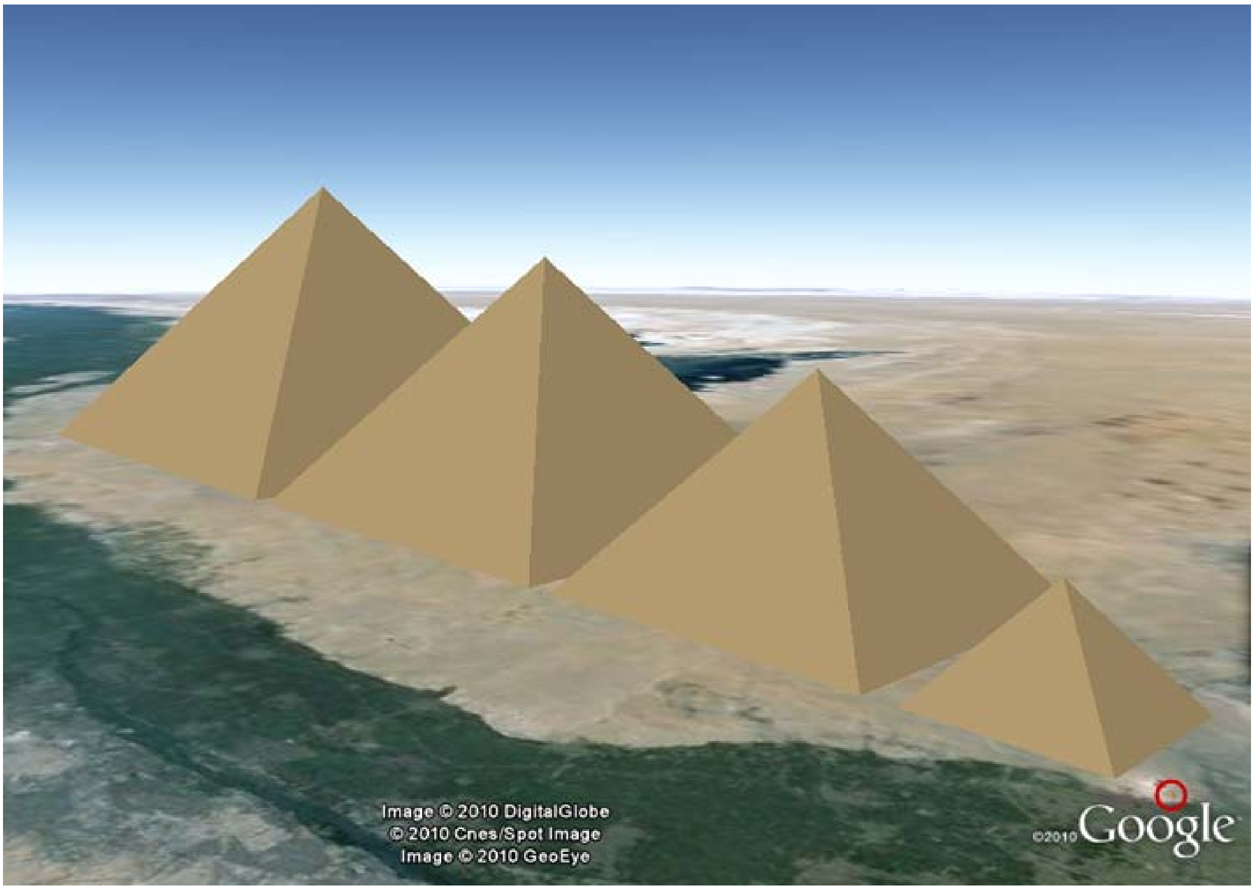

Figure C.1 Pyramids of timber down the Nile. From right to left: 1 (circled in red) to 5 see Table C.1

Source: User created image using Google Earth (2010b) and Google Sketchup (2010).

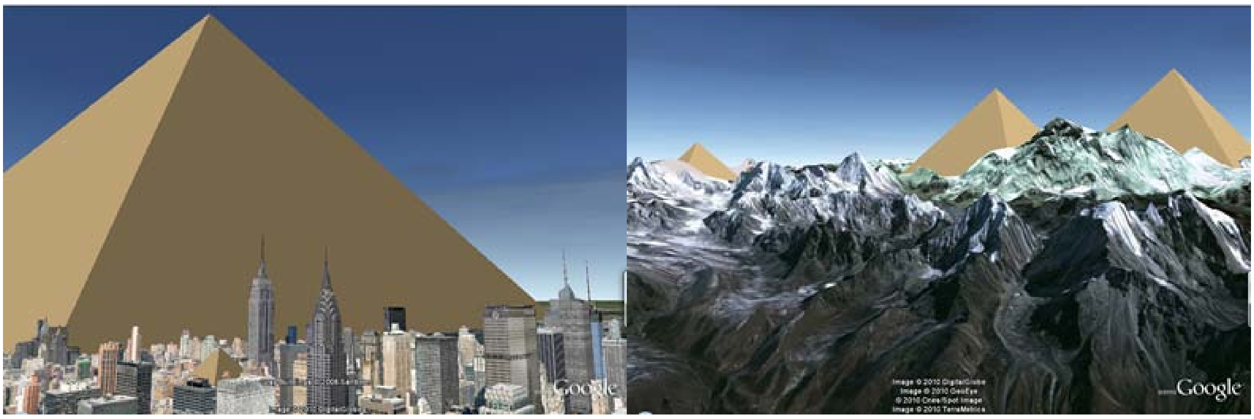

Figure C.2 Above left Pyramid Number 2 (Annual emissions in New York city) Source: Google Earth (2010c). Above right From left to right, Pyramids number 3 – 5. (4 and 5 are behind Mount Everest).

Source: User created image using Google Earth (2010a) and Google Sketchup (2010).

Appendix D Agroforestry trees

Key climatic zone:

1 = Highland sub-humid: altitude over 1000 metres, annual rainfall 500 to 1200 mm

2 = Sub-humid wooded savannah: annual rainfall 900 to 1200 mm

3 = Semi-arid shrub savannah: annual rainfall 500 to 900 mm

4 = Semi-arid tree steppe: annual rainfall 150 to 500 mm

Table D.1 Agroforestry Trees

Scientific Name	Common name	Climatic zone	Suitable for: (soils)
Acacia catechu	Betel-nut palm	1,2,3	No information
A. eliator	River acacia	3,4	No information
A. holosericea	Candelabra wattle	2	No information
A. karroo	Cape thorn tree		Shallow, saline, alkaline, heavy or light soils with a low water table
A. mearnsii	Late black wattle	1,2	Infertile, acid soils with a low water table.
A. melanoxylon	Tasmanian blackwood	1	Periodically waterlogged or flooded light soils
A. mellifera	Black thorn	1,3,4	Shallow, alkaline, heavy or light soils with a low water table
A. nilotica	Babul acacia	1,2,3,4	Saline, infertile, alkaline heavy or light soils, which are periodically waterlogged or flooded
A. saligna	Orange wattle	1,2,4	Shallow, saline, infertile, alkaline soils with a low water table
A. Senegal	Gum arabic	1,2,3,4	Shallow, acid or alkaline, light soils
A. seyal	Shittim wood	3,4	Shallow, infertile, alkaline, heavy or light soils
A. tortilis	Umbrella thron	1,2,3,4	Shallow, saline, infertile, alkaline, light soils with a low water table

Table D.1 Agroforestry Trees

Scientific Name	Common name	Climatic zone	Suitable for: (soils)
Acrocarpus fraxinifolius	Pink cedar	1,2	Soils with a low water table
Adansonia digitata	Baobab	3,4	Infertile, acid or alkaline, periodically waterlogged or flooded soils with a low water table
Afzelia quanzensis	Lucky bean tree	1,2	Soils with a low water table
Agave sisalana	Sisal	1,2,3,4	No information
Albizia lebbeck	Woman's tongue tree	1,2,3	Shallow, saline, alkaline, light soils
Alnus acuminata	Andean alder		Heavy or light soils
A. nepalensis	Nepalese alder	2,3	Acid, heavy or light soils, which are periodically waterlogged or flooded
Anacardium occidentalis	Cashew nut	1,2,3	Infertile, light soils
Annona senegalensis	Wild soursop	2,3,4	Shallow, infertile, light soils
Anogeissus latifolia	Axle wood	2	Alkaline soils, which are periodically waterlogged or flooded
Azadirachta indica	Neem tree	2,3	Shallow, infertile, alkaline, heavy or light soils
Balanites aegyptiaca	Desert date	1,2,3,4	Shallow, infertile, alkaline, heavy or light soils, which are periodically waterlogged or flooded
Bombax costatum	Cotton tree	2,3	Infertile soils, which are periodically waterlogged or flooded
Borassus aethiopicum	African fan palm	2,3	Saline, acid, light soils, which are periodically waterlogged or flooded

Table D.1 Agroforestry Trees

Scientific Name	Common name	Climatic zone	Suitable for: (soils)
Boscia angustifolia	Sehel/Sereh	3,4	Heavy or light soils with a low water table
B. senegalensis	Senegal boscia	4	Infertile, heavy or light soils
Cadaba farinosa	Serein/Suraya	3,4	Shallow, heavy soils
Cajanus cajan	Pigeon pea	2	Saline, infertile light soils
Calliandra calothyrus	Red calliandra	2,3	Infertile, acid, heavy or light soils, which are periodically waterlogged or flooded
Calotropis procera	Sodom apple		Shallow, infertile, heavy soils
Capparis decidua	Kursan/Murkheit	4	Infertile, heavy soils
Carica papaya	Papaw tree	2,3	Acid, light soils
Casuarina cunninghamiana	Casuarina	1	Saline, infertile, acid or alkaline, light soils
C. equisetifolia	Horsetail tree	1,2,3	Saline, infertile, alkaline, light soils
C. glauca	Grey buloke	1	Shallow, saline, infertile, alkaline, heavy or light soils,
Cedrela serrata	Hill toon		No information
Citrus limon	Lemon tree	2,3	Acid, light soils
C. sinensis	Sweet orange	2	Acid, light soils
Cocos nucifera	Coconut palm	3	Saline, alkaline, light soils
Colophospermum mopane	Balsam tree	3,4	Shallow, saline, infertile, alkaline, heavy or light soils with a low water table, which are periodically waterlogged or flooded
Combretum molle	Velvet leaf willow	2	Infertile soils
Commiphora africana	African myrrh	3,4	Alkaline, heavy or light soils

Table D.1 Agroforestry Trees

Scientific Name	Common name	Climatic zone	Suitable for: (soils)
Cordeauxia edulis	Yeheb nut	4	No information
Cordia africana	Large-leaved cordia	2,3	No information
Croton macrostachys	Broad-leaved croton	1,3,4	Light soils
C. melagocarpus	Croton	2	No information
Cupressus lusitanica	Cypress	1	No information
Dalbergia melanoxylon	African ebony	2,3	Shallow soils
D. sissoo	Indian rosewood	1,2,3	Light soils, which are periodically waterlogged or flooded
Delonix elata	White gul mohur	3	No information
D. regia	Flamboyant	1	No information
Dichrostachys cinerea	Marabou thorn	1,2,3	Shallow, saline, acid, heavy or light soils
Dovyalis caffra	Kei apple	2,3	No information
Entada abyssinica	Abyssinia entada	2,3	Shallow soils
Erithrina abyssinica	Lucky bean tree	1,2,3	No information
Eucalyptus camaldulensis	Red river gum	1,2,3,4	Saline, infertile, acid, heavy or light soils, which are periodically waterlogged or flooded
E. globules	Blue gum tree	1	No information
E. tereticornis	Forest red gum	1	Acid, light soils
Euphorbia tirucalli	Pencil tree/milk bush		Shallow, infertile, light soils
Faidherbia albida	Ana tree	1,2,3,4	Light, saline soils
Ficus thonningii	bark-cloth fig		No information

Table D.1 Agroforestry Trees

Scientific Name	Common name	Climatic zone	Suitable for: (soils)
F. sycomorus	Wild fig	2,3	Light soils
Gleditsia triacanthos	Thorn tree	1,2,3	Saline, acid or alkaline, heavy or light soils, which are periodically waterlogged or flooded
Gliricidia sepium	Mother of cocao	1,2	Infertile, acid and alkaline soils, which are periodically waterlogged or flooded
Gmelina arborea	Gmelina	2	Acid or alkaline, light soils
Grevillea robusta	Silky oak	1,2	Acid, light soils
Grewia tenax	Gaddeim/Godem	3,4	Infertile, heavy or light soils
Hagenia abyssinica	Kousso	1	No information
Hyphaene thebaic	Doum palm		Heavy or light soils, which are periodically waterlogged or flooded
Jacaranda mimosifolia	Jacaranda		Light soils
Jatropha curcas	Chinese castor oil	2,3,4	Shallow, infertile soils
Juniperus procera	African pencil cedar	1,2,3	No information
Khaya nyasica	African mahogany		No information
K. senegalensis	African mahogany	2,3	Acid soils
Leucaena leucocephala	Wild tamarind	1,2,3	Infertile, alkaline, heavy soils
Maesopsis eminii	Umbrella tree	2	Light soils
Mangifera indica	Mango tree	3	Light soils
Manihot glaziovii	Tree cassava		No information
Markhamia lutea	Markhamia	3	No information

Table D.1 Agroforestry Trees

Scientific Name	Common name	Climatic zone	Suitable for: (soils)
Melaleuca quinquenervia	Cajeput-tree	1,3	Saline, infertile soils, which are periodically waterlogged or flooded
Melia azedarach	Bead tree	1,2,3	Shallow, saline, infertile, acid, light soils
Moringa oleifera	Drumstick tree	1,2,3,4	Shallow, acid, heavy or light soils
Morus alba	White mulberry tree	1	Acid, light soils
Olea capensis	East African olive		No information
Parkia biglobosa	African locust bean	1,2,3	Infertile, acid, light soils
Persea Americana	Avocado tree	2	Light soils
Phoenix dactylifera	Date palm	3,4	Saline infertile, light soils, which are periodically waterlogged or flooded
Pinus caribaea	Caribbean pine		No information
Pithecelobium dulce	Bread and cheese tree		Shallow, saline, acid, heavy or light soils, which are periodically waterlogged or flooded
Polyscias fulva	Parasol tree		No information
Prosopis africana	Abu suruj	3	No information
P. chilensis	Mesquite/Algarrobo	1,2,3,4	Shallow, saline infertile, alkaline, light soils
P. cineraria	Ghaf	4	Shallow, acid, light soils, which are periodically waterlogged or flooded
Prunus africana	Red stinkwood	1	No information
Psidium guajava	Guava tree	1,2	Acid or alkaline, light soils, which are periodically waterlogged or flooded

Table D.1 Agroforestry Trees

Scientific Name	Common name	Climatic zone	Suitable for: (soils)
Pterocarpus angolensis	African teak	1,2,3	Shallow, infertile, light soils
P. lucens	Barwood	3,4	Shallow, heavy or light soils, which are periodically waterlogged or flooded
Rauvolfia caffra	Quinine tree	2,3	No information
Robinia pseudoacacia	Robinia	1,2,3	Saline, alkaline, light soils, which are periodically waterlogged or flooded
Salvadora persica	Mustard tree	1,2,3,4	Saline, acid, heavy soils
Schinus molle	Pepper tree	1,2,3	Saline, alkaline, light soils, which are periodically waterlogged or flooded
Schinziophyton rautanenii	Featherweight tree	1	Alkaline soils
Sclerocarya birrea	Marula tree	2,3,4	Infertile, light soils, which are periodically waterlogged or flooded
Senna siamea	Black-wood cassia	1,2,3	Acid or alkaline, light soils with a low water table
S. spectabilis	Yellow shower	4	Light soils
Sesbania grandiflora	Flamingo bill	2,3	Acid or alkaline light soils, which are periodically waterlogged or flooded
S. sesban	Egyptian rattle pod	1,2,3	Saline, acid, heavy soils, which are periodically waterlogged or flooded
Syzygium cuminii	Black plum tree	2,3	periodically waterlogged or flooded soils
Tamarindus indica	Tamarind tree	2,3	Saline, acid, light soils
Tamarix aphylla	Leafless tamarisk	3,4	Saline, infertile, alkaline, heavy or light soils

Table D.1 Agroforestry Trees

Scientific Name	Common name	Climatic zone	Suitable for: (soils)
Terminalia brwonii	Harar tree	3	No information
T. catappa	Indian almond tree	2	Saline, alkaline, light soils
Trema orientalis	Charcoal tree	2	Shallow, infertile, acid, light soils
Vernonia amygdalina	Bitter leaf	1,2	Shallow, alkaline, light soils
Vitellaria paradoxa	Shea butter tree	1,2	Alkaline, light soils with a low water table
Vitex doniana	Black plum	1,2,3	No information
Ximenia Americana	Wild plum	2,3	Light soils
Ziziphus mauritiana	Common jujube	1,3,4	Shallow, saline, infertile, acid, light soils, which are periodically waterlogged or flooded
Z. mucronata	Buffalo thorn	1	Acid, light soils, which are periodically waterlogged or flooded

Source: Agroforestry in Africa (n.d.) in Hove (2010)

Appendix E SOC and SIC content of world soils

Table E.1. SOC and SIC content of world soils based on the USDA classification system and FAO classification system. World soil types and carbon content with the predominate soils of the MENA deserts highlighted in grey

Soil order USDA classification	Soil order FAO classification match.	Area worldwide (million km^2)	SOC		SIC	
			Density (t ha^{-1})	Pool (Gt)	Density (t ha^{-1})	Pool (Gt)
Alfisols	Luvisols Planosols	12.6	125	158	34	43
Andisols	Andosols	0.9	220	20	0	0
Aridisols	Solonchaks Solonetz Gypsisols Durisols Calcisols Arenosols	15.7	38	59	290	456
Entisols	Regosols	21.1	42	90	124	263
Gelisols (frost within 1 metre)		11.3	281	316	6	7
Histosols	Histosols	15.3	1170	179	0	0
Inceptisols	Gleysols	12.9	148	190	26	34
Mollisols	Chernozems Phaeozems Kastanozems Luvisols Planosols Solonetz	9.0	134	121	96	116
Oxisols	Ferralsols Nitisols	9.8	128	126	0	0

Soil order USDA classification	Soil order FAO classification match.	Area worldwide (million km^2)	SOC		SIC	
Rocky land		13.1	17	22	0	0
Shifting sand		5.4	4	2	9	5
Spodosols (Spodic horizon)		3.4	191	64	0	0
Ultisols	Nitisols Plinthosols Acrisols Alisols	11.1	124	137	0	0
Vertisols	Vertisols	3.2	133	42	50	21
Total		130.8		1526		945

Source: Lal (2004b); Deckers et al. (2002)

Appendix F Desalination and energy requirements of the MENA nations.

Table F.1 Predicted desalination requirement and energy use of the individual MENA nations in 2050

	Predicted desalination requirement 2050 ($km^3\ yr^{-1}$)	Energy for predicted desalination requirement in 2050 ($TWh\ yr^{-1}$) (3.4 $kWhm^{-3}$ of water in cogeneration)
Morocco	0.3	1.2
Algeria	1.0	3.3
Tunisia	0.3	1.0
Libya	7.3	25.1
Egypt	75	256.8
Oman	1.8	6.2
Kuwait	1.7	5.8
Qatar	0.8	2.7
Saudi Arabia	29.7	101.8
UAE	4.6	15.6
Yemen	18.0	61.8
Bahrain	0.5	1.7
Israel	1.0	3.5
Jordan	1.0	3.5
Lebanon	<0.1	<0.1
Syria	12.2	41.7
Iraq	3.8	13.2
Total	**159**	**545**

Source: Trieb et al. (2005b, pp.144 and A-1 - A-25).

Appendix G EU members and MENA nations and others included in the DLR Studies.

Table G.1 Nations involved in the DLR Studies. Source data: DLR, 2005 and 2006

Country	EU Member	MENA Nation	DLR Study
Algeria		Yes	Med-CSP
Austria	Yes		Trans-CSP
Bahrain		Yes	Med-CSP
Belgium	Yes		Trans-CSP
Bosnia and Herzegovina			Trans-CSP
Bulgaria	Yes		Trans-CSP
Croatia			Trans-CSP
Cyprus	Yes		Med-CSP
Czech Republic	Yes		Trans-CSP
Denmark	Yes		Trans-CSP
Egypt		Yes	Med-CSP
Finland	Yes		Trans-CSP
France	Yes		Trans-CSP
Gaza Strip		Yes	Med-CSP
Germany	Yes		Trans-CSP
Greece	Yes		Med-CSP & Trans-CSP
Hungary	Yes		Trans-CSP
Iceland			Trans-CSP
Iran		Yes	Med-CSP
Iraq		Yes	Med-CSP
Ireland	Yes		Trans-CSP
Israel		Yes	Med-CSP

Country	EU Member	MENA Nation	DLR Study
Italy	Yes		Med-CSP & Trans-CSP
Jordan		Yes	Med-CSP
Kuwait		Yes	Med-CSP
Lebanon		Yes	Med-CSP
Libya		Yes	Med-CSP
Luxembourg	Yes		Trans-CSP
Macedonia			Trans-CSP
Malta	Yes		Med-CSP
Montenegro			Trans-CSP
Morocco		Yes	Med-CSP
Netherlands	Yes		Trans-CSP
Norway			Trans-CSP
Oman		Yes	Med-CSP
Poland	Yes		Trans-CSP
Portugal	Yes		Med-CSP & Trans-CSP
Qatar		Yes	Med-CSP
Romania	Yes		Trans-CSP
Saudi Arabia		Yes	Med-CSP
Serbia			Trans-CSP
Slovakia	Yes		Trans-CSP
Slovenia	Yes		Trans-CSP
Spain	Yes		Med-CSP & Trans-CSP
Sweden	Yes		Trans-CSP
Switzerland			Trans-CSP
Syria		Yes	Med-CSP

Country	EU Member	MENA Nation	DLR Study
Tunisia		Yes	Med-CSP
Turkey			Med-CSP & Trans-CSP
United Arab Emirates		Yes	Med-CSP
United Kingdom	Yes		Trans-CSP
West Bank		Yes	Med-CSP
Yemen		Yes	Med-CSP

Source: Trieb et al. (2005b); Trieb et al. (2006)

Appendix H What are ecosystem services?

Provisioning Services are ecosystem services that describe the material outputs from ecosystems. They include food, water and other resources.

- **Food:** Ecosystems provide the conditions for growing food – in wild habitats and in managed agro-ecosystems.
- **Raw materials:** Ecosystems provide a great diversity of materials for construction and fuel.
- **Fresh water:** Ecosystems provide surface and groundwater.
- **Medicinal resources:** Many plants are used as traditional medicines and as input for the pharmaceutical industry.

Regulating Services are the services that ecosystems provide by acting as regulators e.g. regulating the quality of air and soil or by providing flood and disease control.

- **Local climate and air quality regulation:** Trees provide shade and remove pollutants from the atmosphere. Forests influence rainfall.
- **Carbon sequestration and storage:** As trees and plants grow, they remove carbon dioxide from the atmosphere and effectively lock it away in their tissues.
- **Moderation of extreme events:** Ecosystems and living organisms create buffers against natural hazards such as floods, storms, and landslides.
- **Waste-water treatment:** Micro-organisms in soil and in wetlands decompose human and animal waste, as well as many pollutants.
- **Erosion prevention and maintenance of soil fertility:** Soil erosion is a key factor in the process of land degradation and desertification.
- **Pollination:** Some 87 out of the 115 leading global food crops depend upon animal pollination including important cash crops such as cocoa and coffee.
- **Biological control:** Ecosystems are important for regulating pests and vector borne diseases.

Habitat or Supporting Services underpin almost all other services. Ecosystems provide living spaces for plants or animals; they also maintain a diversity of different breeds of plants and animals.

- **Habitats for species:** Habitats provide everything that an individual plant or animal needs to survive. Migratory species need habitats along their migrating routes.
- **Maintenance of genetic diversity:** Genetic diversity distinguishes different breeds or races, providing the basis for locally well-adapted cultivars and a gene pool for further developing commercial crops and livestock.

Cultural Services include the non-material benefits people obtain from contact with ecosystems. They include aesthetic, spiritual and psychological benefits.

- **Recreation and mental and physical health:** The role of natural landscapes and urban green space for maintaining mental and physical health is increasingly being recognized.

- **Tourism:** Nature tourism provides considerable economic benefits and is a vital source of income for many countries.
- **Aesthetic appreciation and inspiration for culture, art and design:** Language, knowledge and appreciation of the natural environment have been intimately related throughout human history.
- **Spiritual experience and sense of place:** Nature is a common element of all major religions; natural landscapes also form local identity and sense of belonging.

Source:Sukhdev et al. (2010, p.33)