Carbon Farming in Hot, Dry Coastal Areas: An Option for Climate Change Mitigation

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Abstract

We present a comprehensive, interdisciplinary project which demonstrates that large-scale plantations of *Jatropha curcas* - if established in hot, dry coastal areas around the world - could capture 17 – 25 tonnes of carbon dioxide per hectare per year from the atmosphere (over a 20-year period). Based on recent farming results it is confirmed that the *Jatropha curcas* plant is well adapted to harsh environments and is capable of growing alone or in combination with other tree and shrub species with minimal irrigation in hot deserts where rain occurs only sporadically. Our investigations indicate that there is sufficient unused and marginal land for the widespread cultivation of *Jatropha curcas* to have a significant impact on atmospheric CO_2 levels at least for several decades.

In a system in which desalinated seawater is used for irrigation and for delivery of mineral nutrients, the sequestration costs were estimated to range from 42 - 63 € per tonne CO_2. This result makes carbon farming a technology that is competitive with carbon capture and storage (CCS). In addition, high-resolution simulations using an advanced land-surface-atmosphere model indicate that a 10,000 km^2 plantation could produce a reduction in mean surface temperature and an onset or increase in rain and dew fall at a regional level. In such areas, plant growth and CO_2 storage could continue until permanent woodland or forest had been established. In other areas, salination of the soil may limit plant growth to 2-3 decades whereupon irrigation could be ceased and the captured carbon stored as woody biomass.

1. Introduction

It is now widely accepted that anthropogenic greenhouse gas emissions are causing an increase in global mean temperature and an acceleration of the global water cycle (IPCC 2007). Unfortunately, in spite of the great threat posed by climate change to the Earth's environment and humankind, global agreements on greenhouse gas reduction have so far been largely ineffective. During the last decade, the emission rate of CO_2 compared with the period 1990-2000 has even accelerated (Le Quéré et al. 2009). Consequently, a variety of geoengineering approaches have been suggested for mitigating climate change. These options may be separated into purely technological approaches such as sun shading, increase of surface albedo by whitening of buildings, and carbon capture and storage (CCS) (Boyd 2008) or bio-geoengineering options (see, e.g., Betts 2007). A comparison of the effectiveness of different proposals can be found in Lenton and Vaughan (2009). However, this analysis disregards feedbacks in the water cycle.

Recently, technological approaches such as CCS have become of great interest, as this technology may permit the reduction of CO_2 emission rates by power plants (IPCC 2005). However, CCS has also been strongly questioned because of the large amounts of energy needed for its implementation, which reduces the efficiency of power plants, and the huge financial investments that this technology requires. As a matter of fact, CCS has only the potential to reduce emissions from power plants but not from other sources. Furthermore, it is not clear yet whether the long-term storage of carbon can really be guaranteed without leakage into the environment.

Therefore, it is reasonable to explore bio-geoengineering approaches designed to change land-surface properties using the natural properties of vegetation. These include either modifications of energy partitioning by different types of vegetation or afforestation measures leading to a reduction in the levels of atmospheric CO_2 and land-surface temperature. Both are options extensively investigated within IPCC (Metz et al. 2007). For instance, Ridgwell et al. (2009) and Doughty et al. (2010) studied the impact of an increase of agricultural crop albedo using global climate models. In mid-latitudes, a consistent reduction of regional temperature of about 0.25 degrees per 0.01 increase in albedo was predicted. Different relationships between these two parameters occur in other regions such as the tropics. However, global climate models are limited with respect to the correct quantitative simulation of land-surface atmosphere feedback and also to the response of the water cycle including precipitation (e.g., Hohenegger et al. 2009). These aspects call for further studies using high-resolution climate models that avoid the parameterisation of convection and that improve the interaction between land-surface heterogeneities and orography with the atmosphere.

One interesting option is afforestation which has several effects, simultaneously. First, carbon sequestration in biomass both above and below ground is a possible mitigation strategy (Metz et al. 2007). In the following discussion, we refer to this bio-geoengineering option as *Carbon Farming*. Secondly, daily surface temperatures may be reduced in subtropical regions due to changes in the surface energy balance. This depends critically on the partitioning of the energy balance into sensible and latent heat fluxes and its feedback to the atmospheric boundary layer (ABL), clouds, and precipitation. Thirdly, a variety of additional effects may be achieved such as the production of bio fuel and nutrients as well as the creation of a healthier environment. However, carbon farming must not compete with food production so afforestation measures should concentrate on land areas such as desert regions that are not likely to be used for conventional farming and which are not salinated by previous unsustainable agricultural practises.

Recently, Ornstein et al. (2009) investigated this idea in desert regions on a global scale. Using a global climate model, they simulated large-scale reductions of surface temperature in the Sahara and the Australian desert. They also studied large-scale feedback processes such as teleconnection. Focusing on *Eucalyptus sp.* plantations, they stated that a significant mitigation of global carbon emission may be achieved if the Saharan or Australian deserts are cultivated. Furthermore, they found that their models predicted a large increase in precipitation in desert regions and related this to the Charney effect (Charney 1975). With respect to irrigation, Ornstein et al. (2009) stated that the extremely valuable aquifers, which are available in some desert regions, should not be further exploited but considered instead the application of recent advances in desalination technology such as reverse osmosis. They discussed the costs and technological requirements to realise such a large-scale, international project covering areas of the order of 10^9 ha.

These results are encouraging and the interest in afforestation for production of biodiesel and application of the Clean Development Mechanism (CDM) is steadily increasing (see, e.g., cdm.unfccc.int, Kumar et al. 2011). However, several caveats remain with respect to technological and scientific aspects: The technologies for realising huge afforestation efforts such as irrigation with desalination plants are still in their infancy. It is not clear whether the carbon sequestering potential of suitable plants such as *Eucalyptus sp.* and *Jatropha curcas* can be maintained over large plantation areas, but ultimately the only way to find out will be to try.

Furthermore, it is well known that coarse-scale global climate models have severe deficiencies when it comes to simulating land-surface-cloud-precipitation feedback. For instance, Hohenegger et al. (2009) demonstrated that coarse-scale models, which require a convection parameterisation, and convection-permitting models (grid resolution < 4 km) even give feedbacks between soil moisture and precipitation *of different sign*. This is a critical issue for the credibility of climate simulations. These results have been refined by Rotach et al. (2009a, b) and Wulfmeyer et al. (2008, 2011) who demonstrated severe deficiencies in models with convection parameterisation when they are applied to mountainous regions or areas with strong land-surface heterogeneity. This is also the case in coastal desert regions.

Therefore, it is highly questionable whether resilient quantitative results concerning land-surface feedback and precipitation can be achieved with models that use convection parameterisation.

Consequently, we are convinced that an analysis of afforestation measures should be based on a thorough transdisciplinary scientific study on a local scale combining an analysis of the costs, the carbon binding potential, and the economic efficiency of these plantations in connection with the CDM. Here, the technological challenges can be studied in more detail and may be complemented and verified by results from plantations. Furthermore, land-surface-atmosphere feedback processes can be studied more realistically using high-resolution models. This combination of modelling efforts is also essential for studying the substainability of carbon farming.

This work is intended to extend previous work in this area and to close an important gap in the analysis of afforestation projects in dry coastal areas. We focus on *Jatropha curcas* because we consider this plant to be one of the more promising and robust plants suitable for desert regions. Also, the authors of this paper have much specialised knowledge of and relevant data for this plant, its potentialities and requirements. That said, we are also well aware that other tree crops, especially *Eucalyptus sp.* or mixtures of various species, may be more suitable in many cases. Mixed crops can include food and fodder crops and also have the advantage that they produce more diverse ecosystems and thus reduce the danger of epidemics and large scale attack by pests. However the methodology and analysis that we apply here to *Jatropha curcas* could, with suitable raw data, be adapted to these other species and mixtures. With this approach and the application of available data, we are aiming at an analysis of the performance of the plantation over a time period of 1-3 decades. This may also provide an appropriate basis for the assessment of the fate of large-scale plantations for up to a century in future research.

This paper is organised as follows: In section 2 we introduce the project strategy and explain the goals and the interactions of the project partners. In section 3, the results of the study are presented. The biomass production and carbon sequestration potential of *Jatropha curcas* plantations is presented in section 3.1; the irrigation, desalination, and energy supply costs in section 3.2; and the impact on the regional climate in section 3.3. An overview of other expected impacts is presented in section 4 followed by some conclusions in section 5.

2. Project Strategy

An extensive, transdisciplinary study was performed to explore the interwoven local technological, economical, and climatological impacts of carbon farming. In particular, the economic potential of this approach with respect to the CDM was studied. First of all, an important condition was laid down namely that carbon farming must not compete with food production, as cropland is becoming increasingly scarce. According to Costanza et al. (1997), only 1.4 billion ha of the approximately 15 billion ha of earth's land area is currently usable for crops. Extrapolating recent trends in population growth and land degradation, this would leave no more than 1100 m^2 to nourish each of the 9billion inhabitants expected by 2050. At present, 1.9 billion ha of former crop land are degraded and unusable or barren. There are also an additional 1 billion ha of desert land in dry coastal areas with minimum night-time temperatures that seldom, if ever, fall below 12°C. Both types of land are potential areas for carbon farming. The dry coastal areas have been degraded over a long period of time due to lack of precipitation or natural water sources. The very low precipitation amounts are caused by large-scale suppression of convection, e.g., by Hadley cell subsidence, or local suppression of convection either by upwelling of cold air by ocean currents or by atmospheric divergence caused by increasing land friction. Therefore, in these “natural deserts” land degradation caused by poor agricultural practises such as inadequate irrigation leading to high salinity of the soil is hardly an issue. However, strategies for minimizing contamination of the soil must certainly be taken into account and are discussed in sections 3.2 and 4.

Decisions regarding the economic and ecological value of carbon farming are possible only if they are based on a comprehensive assessment of the potential benefits and costs. Before large-scale projects can be established in hot dry coastal areas, in-depth plans for their implementation will need to be drawn up.

Figure 1 depicts the carbon farming concept and shows the key processes involved. Our new evaluation of carbon farming takes the following key factors into account:

- the growth of robust plants under extreme weather conditions,
- technical advances in seawater desalination, and
- an understanding of the impact of greening deserts on weather and climate.

Power and desalination plants are located at the coast line of a dry desert. The output of the desalination plant is used for irrigation of the plantations. The operation of the power plant can be supported by burning part of the biomass produced. If the plantation is large enough, onset of dew and rainfall is expected due to the modification of processes associated with the atmospheric boundary layer (ABL). In Figure 1, the ABL top is indicated by the blue hyper surface. The extra precipitation would reduce the amount of water needed for irrigation and create a more moderate local climate.

Our analysis of the environmental impacts was made using a hierarchy of computer models supported by extensive research on the input parameters. We applied the derived climate models to two proposed pilot sites in Oman and Mexico using results from a plantation of *Jatropha curcas* in Egypt. We used primary and secondary data for technical analyses, and created simulations of irrigation requirements and regional land-vegetation-atmosphere feedbacks. The study is complemented by a description of some non-technical constraints and suggestions as to how such a project may be set up and implemented.

3. Results

3.1 Biomass production and carbon sequestration

Many extended coastal desert areas could be cultivated with robust perennial plants, using desalinated sea water. These include trees such as *Acacia saligna*, *Azadirachta indica*, *Eucalyptus camaldulensis*, *Eucalyptus microtheca*, *Moringa oleifera*, *Pongamia pinnata* and *Jatropha curcas*, shrubs such as *Prosopis cineraria*, *Ricinus communis*, and *Simmondsia chinensis*, and reeds and grasses such as *Arundo donax L*, *LIHD-prairie grasses* and *Miscanthus x giganteus*. The trees in this list have been reported to produce an above ground biomass of between 5 – 25 tonnes dry mass per ha per year equivalent to 2.4 – 12 tonnes of carbon per ha per year (Steen and Reed 2004) and the perennial grasses up to 51 tonnes above ground biomass per ha per year (Angelini et al. 2008). Suitably deployed, these plants could transform unused, barren lands into long-term carbon sinks (Fairless 2007). The carbon efficiency of this bio-ecosystem would compare favourably with all other existing processes for carbon storage and sequestration, including the cultivation of bio fuels (Righelato et al. 2007).

Jatropha curcas is a member of the family *Euphorbiaceae*, genus *Jatropha*. The plant is very well adapted to harsh tropical and sub-tropical environments and is capable of growing in hot, hyperarid deserts (Fairless 2007) but, like most plants, optimum growth requires regular, if minimal, irrigation. Unlike many annual crops that have been the subject of centuries of domestication, *Jatropha curcas* is a wild, perennial plant that has received little scientific attention to date. For this reason, performance parameters vary considerably among different provenances, a fact which is of great significance for future domestication programs (Popluechai et al. 2009).

Long term (> 3 years) empirical data on the growth of *Jatropha curcas* from dry coastal areas are not yet available. We therefore estimated biomass production and carbon sequestration from measurements taken on a 100 ha *Jatropha curcas* plantation in Luxor, Egypt (Figure 2) containing 940 plants / ha. The plants in this location are still slightly less than 4 years old, and the site is comparable to a hot, dry coastal area because day temperatures exceed 40°C for 260 days of the year and precipitation is very sporadic with a long-term average of only 0.3 mm per year. Sewage water from the city of Luxor was used for irrigation - not desalinated sea water. The use of such waste water would also be a possibility in some hot, dry coastal areas, but cities of any size are comparatively rare in these places and the amount of water available would not be nearly enough to support the scale of plantations envisaged.

The extensive use of sewage water would also not be recommended in very dry areas because of salination. In the literature, mixed results are found with respect to the sensitivity of *Jatropha* to salinity. Whereas Tal et. (1979) found a very low sensitivity of plant growth on salinity and Silva et al. (2010) found adaptive physiological processes reducing salination-induced stresses; in contrast, Rajaona et al. (2012) observed that salt stress influenced Jatropha's canopy development and the CO_2 assimilation rate. Without extensive flushing, it is unlikely that more than one crop of *Jatropha curcas* could be grown before the build-up of salt in the soil prevented further growth, in which case carbon sequestration could be done only once. However, long-term experience is lacking and there is a need for more experiments and analyses on large-scale plantations.

One issue may be environmental safety, as concerns have been raised in the literature about the invasiveness of the *Jatropha* species. But this is actually only a problem with *Jatropha gossypiitolia* (Achten 2007). Based on our observations in Luxor, Egypt, we do not expect major problems in this respect, as the proliferation of *Jatropha curcas* is confined to the area under irrigation by the neighbouring hot desert areas. Growing *Jatropha curcas* in large-scale monoculture may also involve risks related to plant health. *Jatropha curcas* is largely immune to diseases and pests but insect infestations such as flea beetle (*Aphtona* species) (Holl et al. 2007), whitefly (*B.tabaci*), the leaf and capsule borer (*Pampelia morosalis*) and bugs such as *Scutellera nobilis* and *Chrysocoris purpureus* have been reported in a few cases. It is also susceptible to a number of viral diseases, e.g., the Jatropha Mosaic Virus (www.nri.org/projects/Jatropha). Since only limited empirical data exist concerning the toxicity of *Jatropha curcas* fruits consumed by humans – with the exception of the two edible, non-toxic genotypes, *Jatropha curcas* (Makkar et al. 1998) and *Jatropha platyphylla* (Makkar et al. 2010) – Achten et al. (2007) recommend precautionary measures. The main toxic components of *Jatropha curcas* are the phorbol esters. These are found in all plant parts and act as a protection mechanism against browsing by animals.

From the plantation in Luxor, fifty, 32 month old *Jatropha curcas* bushes were chosen at random from among 94,000. Trunk circumference at ground level and height of each bush were measured to ± 1cm, and the bushes were dug up. Care was taken to include as many of the roots as possible, but very fine root systems were discarded. The bushes were separated into their main morphological components (roots, trunk, and branches). The roots were washed to remove sand and dried and then all components were weighed to ± 0.1kg. After chopping and homogenising the three fractions, samples were taken, placed in sealed plastic bags and sent to Germany where dry mass was determined by heating to constant weight at 105°C over 3-4 days. Carbon content was calculated as 50% of dry mass (see Table 1).

The problem of obtaining longer-term biomass data for Jatropha curcas has already been mentioned. To get reasonable estimates, we used data on the diameter of Jatropha curcas trees quoted by Holl et al. (2007) from trees up to 12 years old and fitted a growth curve to a graph of age versus diameter at ground level (DGL). According to forestry experts, an assumed average rate of growth of DGL of 4mm per year from age 12 on could then yield a 20 year value for DGL of 412 mm. We then used an allometric equation of Sampaio and Silva (2005) for *Jatropha mollissima* in Brazil to calculate the most likely biomass at 20 years. This equation predicted that the average dry biomass would be 140 kg per tree above ground and 55kg below ground.

Recently, Hellings et al. (2012) published allometric equations based on their destructive analysis of Jatropha trees in Northern Tanzania. These authors experienced similar problems to us in that most of their sample trees were 2.5-4.0 years old with just one 7 and one 25 year specimen. However, their results are similar in some respects to ours. For example, their 25 year old tree had a DGL of 433 mm, whereas our predicted value for a 20 year old tree was 412mm. When we applied their allometric equations to a 412mm diameter tree we obtained values of 165 and 146 kg for total and above ground woody dry biomass respectively. The relevant equations were: $TWD = 0.0042\ DGL^{2.8361}$ and $AGWD = 0.0019\ DGL^{3.0248}$ where TWD is Total Woody Dry matter and AGWD is Above Ground Woody Dry matter.

There was good agreement for the prediction of AGWD but the below ground woody biomass (TWD-AGWD) was substantially lower using these equations (19 vs 55kg or 13% vs 28% of TWD). The value of 13% was lower than the value calculated directly from the data in Helling et al. (2012) (28.1% ± 6.5% which includes the 25 year old tree that gave a value of 30.6%), or the data of Firdaus et al. (2010) quoted by Hellings et al. (2012)) which gave values of 24-51%, or that of the data in Table 2 of this paper (average 24.3%).

In view of the above we have used our original estimates in subsequent calculations in this paper viz. a value of 140 kg for the AGWD of a 20 year old tree, which is slightly lower than the value derived from the data of Hellings et al. (2012), and a value of 195 kg for the TWD of a 20 year old tree, which seems consistent with the ratios of AGWD to TWD reported here and elsewhere. We stress that these values are tentative and based on sparse data but subsequent calculations are sufficiently transparent that they can easily be repeated if or when more robust data become available.

At a planting density of 940 trees per hectare a TWD of 195 kg would give a total dry biomass production of 183.3 tonnes over 20 years. Without including the leaves and fruits which, in a hot desert climate accumulate as litter under the trees, this would translate into a total of 91.7 t ha^{-1} of carbon. If we include the fruits and the leaf litter, then the figure for carbon sequestration by a Jatropha curcas plantation could be up to 50% higher reaching about 137.6 t ha^{-1} of carbon by year 20. Note that this estimate does not include possible carbon sequestration in the soil, and the yearly average range of 4.9 – 6.9 t ha^{-1} y^{-1} is well within the range of 2.4 – 12 t ha^{-1} y^{-1} reported above for a variety of perennial desert trees.

In terms of CO_2 sequestration, a range of 4.9-6.9 tonnes ha^{-1} y^{-1} of carbon translates into an average of 21.6 t ha^{-1} y^{-1} of CO_2 or 2.16 kg m^{-2} y^{-1}. We have used this value to estimate the amount of anthropogenic CO_2 that could be removed by the establishment of large-scale Jatropha curcas plantations.

Given the total mass of the atmosphere $m_{atm} \approx 5.13 \times 10^{18}$ kg, the molecular weight of dry air M_D = 28.96 g mol^{-1}, and the molecular weight of CO_2 M_{CO2} = 44.01 g mol^{-1} then the relationship between the mass of CO_2 in the atmosphere (mCO_2) and the volume mixing ratio of CO_2 in dry air (V_{CO2}) is:

$$m_{CO2} \cong m_{atm} \frac{M_{CO2}}{M_D} V_{CO2} \cong V_{CO2}\, 7.8 \cdot 10^{18}\,\mathrm{kg} \qquad (1)$$

Table 2 gives values of V_{CO2}, m_{CO2}, and the corresponding mass of carbon, m_C ($m_C = m_{CO2}$ / 3.67) today and prior to the industrial revolution. From these values we can see that the increase in V_{CO2} over this period was around 105 ppm, which is equivalent to 819 Gt of CO_2.

Using equation (1) and the average value for the amount of CO_2 likely to be sequestered by planting *Jatropha curcas* (2.16 kg m^{-2} y^{-1}), simple calculations allow several interesting and important conclusions to be drawn.

a) Since the present rate of increase of VCO_2 is around 2ppm per year, stabilising VCO_2 at its present level would require the planting of 0.73 x 10^9 ha of *Jatropha curcas* which is just under three quarters of the 10^9 ha of desert and marginal land we estimate to be suitable for *Jatropha curcas* cultivation.

b) If the remaining 0.28 x10^9 ha were also planted, this area would, over a 20 year period, reduce VCO_2 by 17.5 ppm or 16.6 % of the total increase in CO_2 since the industrial revolution.

c) Around 2400 km^2 of *Jatropha curcas* would be required to remove the 5 Mt of CO_2 produced annually by a typical, modern, coal fired power station (1000 MW, 5000 full load hours, 45 % net electrical efficiency) and 69,400 km^2 would absorb all the CO_2 produced by motor vehicles in Germany (about 150 Mt per year).

The predicted reduction levels in CO_2 can be achieved as long as the plants are growing at the expected rate for 1-3 decades. Therefore, carbon farming has the potential to influence the atmospheric CO_2 level at least over this time period. The fate of large-scale plantations beyond this time period needs more research and experiments. Some options are discussed in section 4.

3.2 Irrigation, desalination, energy supply and associated costs

The plants in Luxor were irrigated with an open-line sub-surface irrigation system that delivered 20 litres of water per plant every 7 days during the hot season (240 days) and every 10 days during the cold season (125 days) which was enough for optimum plant growth. This translates into roughly 880 m^3 ha^{-1} y^{-1} for 940 plants ha^{-1}, which corresponds to < 100 mm y^{-1}. The root system of the plants that were harvested at 32 months typically covered an area of less than 1 m^2 so this type and level of irrigation was equivalent to 880 mm y^{-1} over this area.

This level of irrigation is rather more than that recommended for *Jatropha curcas* by Gebel and Yüce (2008) who suggest using 17,500 m^3 d^{-1} for a 10,000 ha plantation which works out at 639 m^3 ha^{-1} y^{-1}. Application of the FAO CropWatmodel using data from Holl et al. (2007) also gave similar results. This simulation takes into account local temperatures and rainfall. It gave results that were 10% higher than our Luxor data for a proposed site in Oman and 50%

less for a proposed site in Mexico where annual rainfall was appreciably higher than that in either Oman or Luxor.

The harvested trees had no discernible tap roots, and the soil outside the area watered by the irrigation system was dry indicating that no other source of water such as ground water was available to the plants.

Sewage water as used in the Luxor project will also provide the plants with nutrients. According to the analyses quoted by Hussein et al. (2004) the treated effluent contains 22.0, 3.8 and 22.4 ppm of N, P and K respectively. The quantity of water applied to the plants (ca. 900 m^3 ha^{-1} y^{-1}) would provide 19.8, 3.4 and 20.2 g of N, P, and K respectively to each plant per year. These amounts plus the nutrients available from the soil were enough to promote healthy plant growth. In our proposed system using desalinated water, these and other essential minerals would have to be provided dissolved in the irrigation water.

Over recent decades, seawater desalination has become technically and economically feasible. The two main techniques currently used in large scale plants are illustrated in Figure 3. The essential difference between the two desalination methods is the form of energy needed for the separation of water from salt. While thermal desalination (TD) processes need both heat to evaporate the water and electricity to pump it, reverse osmosis (RO) only uses electricity for the high pressure pumps that overcome the osmotic pressure of seawater. Based on the experiences gained in Luxor we could assume that, after an initial growth phase of about three years, biomass would begin to accumulate in the form of trimmings, withered leaves and nuts. This biomass can be used as an energy source. According to Gebel and Yüce (2008), 5 metric tons of dry biomass with a heat of combustion of 18.5 MJ kg^{-1} becomes available per hectare per year in the form of nuts, leaves, and trimmings. This material from a 10.000 ha plantation could therefore be burnt to produce a continuous heat output of 30.000 kW. This material has not been included in the estimation of carbon sequestration and would provide enough energy to produce steam either as the first stage in a thermal desalination plant or to drive a turbine to generate electricity for a RO plant.

Several thousand desalination plants of various capacities presently operate worldwide producing more than 50 million m^3 of desalinated water per day. The largest plants are usually coupled directly to a power station for their energy supply and deliver around 50,000 m^3 d^{-1} per unit. The total energy needed to desalinate sea water can be as little as 5 kWh m^{-3} for a large state-of-the-art reverse osmosis desalination plant (Shannon et al. 2008). The fresh water produced is used in industry, agriculture and the home.

To estimate the costs of the carbon farming method proposed above, we consider a *Jatropha curcas* plantation of 10,000 ha. It is assumed that the plantation is started on virgin desert land and cultivated over a period of 20 years. For the climate simulations the locations of the plantation are arbitrarily chosen to be in Oman and Mexico. Based on data from the plantation in Luxor, Egypt, the annual water demand by *Jatropha curcas* planted at 940 plants ha^{-1} is 880 m^3 ha^{-1} y^{-1}. For a plantation of 10,000 ha practising placed irrigation, this would mean 24,109 m^3 d^{-1}. The nominal capacity of a suitable desalination plant should therefore be around 25,000 m^3 d^{-1}.

There are many and varied estimates of the cost of desalinated water. Yerimiyahu et al. (2007) gives a figure of 0.55 US$ (0.42 €) per m^3 of drinking water and Methnani (2007) states that most estimates for the cost of water in "mega projects" are of the order of 0.5 € per m^3. Methnani's own calculations using the DEEP program of the International Atomic Energy Authority give values of 0.53-0.72€ m^{-3} and 0.85-1.28€ m^{-3} for RO and TD plants respectively when the energy source is a combined heat and power plant (CC) fuelled by fossil fuel. Corresponding figures when the energy source is an (atomic) high temperature gas reactor (HTGR) are 0.42-0.52€ m^{-3} for RO and 0.44-0.54€ m^{-3} for TD. These figures show that the cost of producing desalinated water depends very much on the cost of the energy source and is particularly vulnerable to changes in the price of fossil fuel if a CC plant is used. One of the major advantages of the kind of carbon farming proposed here is that the project produces its own fuel after the third year in the form of tree trimmings and is thus relatively immune to the escalating price increases that will become inevitable as fossil fuels become rarer and more costly to extract. In our analysis, producing the fuel comes under the operational costs for the plantation so the cost of the desalinated water is mostly incurred for building, running and maintaining the machinery. This cost is therefore likely to be much closer to Methnani's HGRT estimates than those for CC and probably even lower since an atomic reactor is not required. We therefore use a global figure of 0.5€ m^{-3} in all subsequent calculations.

The carbon farming costs are estimated using the results from the Luxor plantation and other pilot *Jatropha curcas* plantations in India and Madagascar. The costs include land lease (10 € ha^{-1} yr^{-1}), running the plantation including establishment and cultivation (200 € ha^{-1} yr^{-1}), erecting and running the irrigation system (100 € ha^{-1} yr^{-1}) and other running costs not connected with water (310 € ha^{-1} yr^{-1}). With an annual water demand of 880 m^3 ha^{-1} yr^{-1}, the total running costs would be 1060 € ha^{-1} yr^{-1}. In the coming 20 years, 92 - 138 t C ha $^{-1}$ can be sequestered equivalent to capturing 338 - 506 t CO_2 ha^{-1} from the atmosphere. Thus, the total cost for carbon farming would be 42 - 63 € t $^{-1}$ CO_2, which is similar to the cost estimates of conventional CCS technology which are around 54 € t^{-1} CO_2 (IPCC 2005).

We estimate that it would take around 3 years before the plantation could provide enough spare biomass in the form of trimmings to produce the necessary heat to run the desalination plant (either directly in the case of TD or indirectly to run a generator for a RO plant). Until that time, the shortfall in energy would have to come from older, more mature plantations, from the electricity grid or from other sources. The biomass burned would release carbon as CO_2, but this would be a small amount compared with the total carbon sequestered as biomass. Another obvious option would be the use of solar power plants.

3.3 Impacts on regional climate

3.3.1 Feedback processes in desert regions

Charney (1975) proposed self-stabilization effects in subtropical deserts related to feedback processes between surface albedo and precipitation. Prentice et al. (1992) extended this research by considering the feedback processes between vegetation and the hydrological cycle. By coupling a climate model to a dynamic vegetation model (Claussen 1994) and application of conceptual models (Brovkin et al. 1998), two stable regimes were found in the Sahara: a desert equilibrium with low precipitation and absent vegetation and a green equilibrium with moderate precipitation and permanent vegetation cover. The impact of greening the planet on global temperature was studied by Kleidon et al. (1999). They demonstrated that greening the planet would result in a reduction of global mean surface temperature mainly due to enhanced surface evapotranspiration in combination with a modification of the global water cycle.

In the subtropical regions, which are under consideration in this work, a change of weather conditions can also be expected, as large-scale effects are produced by subsidence caused by the Hadley circulation while significant horizontal moisture transport is present at least in the summer season. In Oman, these effects are due to humid air advected from the south over the Arabian Sea whereas in Mexico, moist air is transported from the Gulf of Mexico to the Sonora desert. These events are a prerequisite for the induction of precipitation processes. However, the greening of the desert by a plantation with low levels of irrigation has more influence on the sensible heat flux and on changes of the atmospheric flow than on a change of evapotranspiration in the region of the plantation. Consequently, greening dry coastal areas has the potential to mitigate climate change, curb desertification, localise regional water cycles, and, consequently, promote rural development.

3.3.2 Model Set up

To investigate whether the scenario mentioned above was likely to occur in large-scale *Jatropha curcas* plantations, we used a specially adapted land-surface-vegetation-atmosphere model and applied it to two proposed pilot sites in Oman and Mexico. The study was executed with the Weather Research and Forecasting (WRF) model version 3.1 coupled to the NOAH[1] land surface model (LSM) (Chen and Dudhia 2001). In order to minimize systematic errors due to large-scale conditions, WRF-NOAH was driven by European Centre for medium-Range Weather Forecasts (ECMWF) analyses with a resolution of T799 (about 12.5 km grid resolution in the domains of interest). The nested domain was chosen to be a few tens of km larger than the planted region in the centre of the high-resolution domain. At the boundaries, one-way nesting was applied because we assumed that the scale of the planted region was still too small to induce large-scale feedback processes to the exterior domain.

As far as possible, the physics of WRF-NOAH was adapted to the physics of the ECMWF model for minimizing inconsistencies at the boundaries and the interior of the nested regions. The WRF physics included the short-wave and the long-wave radiation schemes of Dudhia (1989) and Mlawer et al. (1997), respectively, the Yonsei University boundary layer parameterisation (Hong et al. 2006), and the two-moment cloud microphysics of Morrison et al. (2009). Deep and shallow convection were not parameterised.

To obtain simulations with optimal performance, WRF was operated with a convection permitting grid resolution of about 4 km. This scale was chosen in order to simulate feedback processes between areas with different land-surface properties, atmospheric boundary layer (ABL), convection initiation, clouds and precipitation as realistically as possible. Recent

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[1] NOAH: joint land-surface model of N = National Center for Environmental Prediction (NCEP); O = Oregon State University (Dept of Atmospheric Sciences); A = Air Force; and H = Hydrologic Research Lab – NWS (National Weather Service) (now Office of Hydrologic Division)

results of convection-permitting simulations confirm their superior performance compared to models with convection parameterisation with respect to the resolution of land-surface heterogeneity and orography (Schwitalla et al. 2008; Wulfmeyer et al. 2008; Rotach et al. 2009a, b; Wulfmeyer et al. 2011) and to enhanced forecast skills (Schwitalla et al. 2011; Bauer et al. 2011). Convection-permitting resolution is essential in this study, particularly considering the relatively small spatial domain of the *Jatropha curcas* plantation. This was set to about 100 km x 100 km oriented along the coast lines in both regions, Oman and Sonora (see Table 3).

A key accomplishment of this study was the optimization of an advanced land-surface model (LSM), in this case that of NOAH, in the regions of interest. This required an accurate description of sub-surface and surface soil properties and vegetation which we achieved by applying an advanced 20-category vegetation-land-use data set (Friedl et al. 2002). Several improvements were implemented in the LSM in order to achieve the most realistic results. These included modification of the vegetation parameters to make them appropriate for *Jatropha curcas* and simulation of constant, regular irrigation. At the date of this study, a detailed parameter table for *Jatropha curcas* was not available. However, as the vegetation properties of *Jatropha curcas* are close to *Evergreen Broadleaf Forest* (land-use category 2), we started with this data set and optimized all parameters by a thorough study of recent published vegetation properties of *Jatropha curcas* (Gupta et al. 2002, Holl et al. 2007, Viña et al. 2004). The main differences from land-use category 2 are the maximum leaf-area index (3.2 instead of 6.48) and the minimum stomatal resistance (130 s m^{-1} instead of 150 s m^{-1}). The main difference between the vegetation and desert is that the albedo is lower in the former from 0.38 to 0.12, but the increase of the roughness length from 0.01 m to 0.5 m can also play a role in the development of convection in the target regions. This translates into different energy partitioning over the plantations. The remaining differences were not considered critical for this study, as these were expected to affect the resulting impact of the vegetation cover on atmospheric variables only at a secondary level.

Another special requirement was a reasonable estimate of the effect of irrigation. It turns out that irrigation has a negligible effect on the evapotranspiration, as long as the irrigation amounts derived in section 3.2 are realistic. This is due to the fact that an irrigation of about 100 mm/yr = 0.27 mm/day, which is taken as reasonable approximation from section 3.2 (Holl, 2007; Gebel and Yüce, 2008) translates into a ratherlow upper limit of transpiration during daytime: 0.27 mm/day = 0.27 mm/(12 * 60 * 60 s) ≅ 16 W/m^2. This result may be modified, if further data concerning vegetation dynamics and irrigation amounts become available. However, even if errors of around 100 % are made, the partitioning of fluxes in the energy balance closure remains mainly driven by the sensible heat flux, which amounted to more than 500 W m^{-2} during daytime both in Oman and Sonora. Consequently, area averaged irrigation of the soil in the grid cell could be neglected and details of irrigation techniques did not have to be altered so that the soil moisture was kept the same as the initial values specified in the ECMWF driving data. Furthermore, the resulting low latent heat flux minimizes potential errors with respect to the assumptions made as to soil properties such as hydraulic conductivity. It is also worthwhile to point out that during our simulations the soil moisture remained very low but was still, with values of about 0.08, higher than the wilting point of loam (0.06) or sandy loam (0.047) which are the dominant soil types in the regions of interest. This demonstrates once again the consistency and reality of our results. Finally, care had to be taken to ensure the correct simulation of the vegetation in each grid cell of interest. A corresponding vegetation mask was developed and carefully tested in order to make sure that changes in land surface properties implemented in the model system exactly matched those in the regions selected in Oman and Sonora (Mexico).

Figure 4 demonstrates the successful implementation of the modified land-use parameters in the LSM. The soil type in both Oman and Mexico was similar across the respective regions and the locations of the plantations at the coasts are easily detected due to changes in albedo.

3.3.3 Results

The model system was operated for a full year (2007) in order to detect feedback processes with high statistical confidence during all seasons. Four simulations were performed for the whole of 2007: Oman CONTROL (no changes of vegetation properties), Oman IMPACT (modification of land-surface properties by planting with *Jatropha curcas* in selected region), Sonora CONTROL, and Sonora IMPACT. The year 2007 was chosen, as typical weather prevailed and the most advanced and recent driving data could be used. For each simulation, seasonal averages and mean diurnal cycles with their corresponding standard deviations were determined for surface flux and atmospheric variables. The boundary layer depth, the cloud coverage, the rain rate, and the formation of dew were also analysed.

The differences in albedo and transpiration between CONTROL and IMPACT lead to substantial changes in surface variables and atmospheric boundary layer (ABL) development. The diurnal cycles of the surface heat and the latent heat fluxes were substantially enhanced, particularly in summer. Whereas the latent heat flux was almost positive throughout the day, it became negative during night time in spring, fall, and winter. This effect led to the formation of dew. For instance, in Oman, the formation of dew amounted to 46 g m^{-2} per night. Dew can be used by plants thus reducing the amount of water that has to be provided by irrigation. The exact amount, however, will be subject of future experiments and investigations.

The mean average surface temperatures over the *Jatropha curcas* plantations in both Oman and Mexico fell by more than 1°C during all seasons. This effect was due to a nonlinear modification of the diurnal cycle of the sensible heat flux. We attribute the stronger cooling during night time to the high emissivity of the plants. The increase of surface temperature during daytime was overcompensated by a reduction of temperature during night time resulting in a decrease in mean temperature.

Another substantial effect was an increase of the atmospheric boundary layer (ABL) depth, particularly during summer time. This is demonstrated in Fig.5, which shows the spatially resolved difference between the IMPACT and CONTROL planetary boundary layer depth (PBLH) over Oman and the Sonora. The mean PBLH over the plantations rose by more than 250 m. The modification of the ABL depends on the local upstream conditions (wind speed and wind shear), the land surface energy balance closure (EBC, which was quite similar over both plantations), the local vertical stability of the ABL, the strength of the capping inversion, and the subsidence in the free troposphere. These effects resulted in a growth of a thermal internal ABL over the plantation on the upwind side and wake effects downstream of the plantations. Interestingly, in the Sonora and Oman an increase and a decrease of the ABL were found downstream of the plantations, respectively. These complex and non-linear effects are currently the subject of further studies. The increase of the ABL depth due to the higher sensible heat flux over the plantations caused a strong diurnal cycle. In the Sonora, at local noon, the ABL increased from 1800 m to 2580 m between CONTROL and IMPACT and, over Oman, the corresponding increases were 2000 m to 2750 m, respectively. The mean ABL increased from 750 m to 976 m in Oman and from 685 m to 895 m in the Sonora. These increases mainly occurred during daytime.

Simultaneously, the increased latent heat flux caused more moisture to be mixed vertically in the ABL. In combination with the enhanced ABL depth, this led to an increased likelihood reaching the lifting condensation level in the ABL. Consequently, vertical stability was reduced increasing the probability of deep convection during summer time (June, July, August) both in Oman and Sonora.

Figure 6 shows the predicted changes in precipitation over 100 km x 100 km *Jatropha curcas* plantations in both regions. Changes in rainfall were complex and tended to occur in streaks due to several events where convection was initiated. The increase in rainfall is substantial in summer and can amount to 160 mm along the streaks. This localization of the water cycle would be very beneficial for the biosphere in this region. Overall, precipitation increased on average by approximately 11 mm and 30 mm in Oman and the Sonora, respectively, and occurred mainly in summer.

Compared with previous studies of land-surface-vegetation-atmosphere feedback processes with respect to precipitation (Charney 1975; Claussen 1994; Brovkin et al. 1998; Ornstein et al. 2009) our model had a much finer resolution. This gave a much deeper insight into the complex chain of processes leading to a positive precipitation feedback over the plantations and, more generally, to a greening of desert regions. The processes simulated in Oman and Sonora leading to precipitation are reliable and reasonable. To our knowledge, this study is the first to simulate the effect of the development of substantial plant cover in a tropical desert region with a specially adapted land-surface-vegetation-atmosphere model at such a fine resolution.

In the future, it is essential that this process chain is studied in more detail and related to the size, shape, and orientation of plantations as well as to the mean air flow. Particularly, it needs to be investigated whether, at a certain size of plantation, a point of self-stability can be reached where the precipitation enhancement is large enough for artificial irrigation to be no longer necessary. The GMC model of Ornstein et al. (2009) proposed increases in precipitation of up to 1400 mm per year for greening the Sahara. However, based on our research and experience with quantitative precipitation simulations, it is essential to confirm this with the new generation of convection-permitting models. In plantations of up to100 km x 100 km, the predictions of our model are much more modest, so *Jatropha curcas* would always require water from desalination. It is for this reason that we have postulated the use of only those desert areas which are near the coast in order to minimise the costs of transporting water to the plants both vertically and horizontally. In any case, the precipitation increase of

11 mm and 30 mm in Oman and the Sonora, respectively, would spare some of the water needed for irrigation by the plantations in the summer season, which was estimated to be 25 mm. It is important to quantify this in connection with the "self-stability" of the plantations. However, it should be noted that the precipitation increase is not the amount that ends up in the root zone for irrigation. This value depends on the runoff, the interception, the evapotranspiration, and the infiltration into the soil. The precipitation increase exhibits a diurnal cycle and, as it is driven by the increase of sensible heat flux, the accumulation of water in the soil depends on the diurnal cycle as well. Therefore, the increase in soil moisture and thus the reduction of water demand depends in a non-linear manner on the temporal and spatial evolution of the single, induced precipitation events. These analyses are beyond the scope of this work and subject of another publication, which is in preparation.

So far, in our simulations, effects on atmospheric variables downstream of the plantations were small. If larger scale plantations are simulated, the teleconnection of weather pattern also needs to be studied by increasing the domain simulated in the model around the plantations substantially or even by global simulations.

4. Other expected impacts

The oil in *Jatropha curcas* nuts is a viable and valuable source of biofuel (Devappa et al., 2010). Harvesting the nuts would reduce the amount of carbon sequestered by the plantation as a whole by about a third but in some situations this would be worthwhile in order to provide local employment and as an additional source of income for the plantation owners.

In some situations, one of the sources of 'income' would be the increase in value of the land on which the *Jatropha curcas* was grown. The provision of a source of water and roads and the growth of vegetation would turn some desert coastal areas into desirable locations for the establishment of towns and villages.

On any proposed site, current land use rights and systems must be carefully checked and respected. Land may be used for occasional grazing, collection of desert fruits and flowers, extraction of minerals and other natural resources, hunting, tourism, cultural and religious uses, military training etc.

Regarding desalination plants, environmental impacts will have to be considered at each specific location. Issues include the topography of the site, off-shore bathymetry, geology / seismology, and environmental concerns especially where brine from the desalination process is returned to the sea.

As mentioned previously, we expect soil carbon stocks to increase as plantations mature. Also, as forests and plantations mature, large amounts of carbon are also sequestered in the soil. Mueller-Landau (2009) states that in African tropical forests the soil holds as much carbon as the trees. Ferric Acrisols in the semi-arid coastal savanna zone of Ghana which is part of the extensive savanna belt of West Africa were found to contain 16-53 tonnes of carbon ha^{-1} under different types of cultivation (Dowuona1a GNN, Adjetey ET (2010). These figures give an idea of the potential for soil carbon storage if one were to start irrigating desert soils from scratch. Although decomposition will tend to reduce soil carbon stocks on a time scale of decades to centuries (Bird et al. 1999), we assume that in a hot, dry desert climate an appreciable portion will not be returned to the atmosphere (Lewis et al. 2009). Therefore, carbon storage as woody organic matter may not a permanent solution but at least it would provide a breathing space during which longer term methods of storage and reduction of CO_2 emissions could be found.

The ultimate fate of the plantations proposed in this paper can only be studied by further extensive experiments. It is probable that the trees on many of them would continue to grow, albeit at an ever decreasing rate, until it was no longer worthwhile irrigating them. At this stage, they could either be harvested or irrigation could be ceased. Harvested material could be stored or used as fuel. Using the material as fuel will, of course, release CO_2 back into the atmosphere so, even if the cleared areas are replanted, the potential for net removal of atmospheric CO_2 will be limited to that achievable in the first 20 years of growth, plus any carbon accumulated in the soil.

The option of storing the material could be achieved most easily by simply ceasing irrigation since the sites proposed for the plantations are hot dry deserts. This would be the only option in sites where the salinity of the soil had accumulated enough after 20 years to inhibit optimal growth. Incidentally, this will almost certainly be the case in our test site in Luxor where the irrigation water derived from sewage is relatively saline and may also contain other undesirable mineral compounds. Once again the amount of carbon sequestered is limited to that accumulated during 20 years.

The most optimistic scenario would be one in which the plantations caused sufficient increase in precipitation, as predicted by our climate model, to maintain vegetative growth and establish permanent woodland or forest without artificial irrigation. On a geological timescale this might even lead to the production of coal or petroleum deposits.

5. Conclusions

We have introduced a transdisciplinary project for simulating the technological, economic and climatological impacts of carbon farming by *Jatropha curcas* plantations in dry coastal areas as well as their usefulness with respect to the Clean Development Mechanism (CDM). We have determined both by estimations and by field measurements that plantations of *Jatropha curcas* if established in hot, dry coastal areas around the world – should be capable of capturing 17 – 25 tonnes of carbon dioxide per hectare per year from the atmosphere (averaged over 20 years). We found that a project to implement these ideas is technically feasible using recent advances in desalination methods such as reverse osmosis. Economically, carbon farming is competitive with carbon capture and storage (CCS). The total cost for carbon farming were estimated to be 42 - 63 € t^{-1} CO_2, which is similar to that of CCS technology (54 € t^{-1} CO_2 (IPCC 2005)). In extensive sensitivity tests, we simulated the carbon sequestration cost in response to changes in market prices, labour requirements and biomass production (factor-by-factor approach). The most sensitive economic factors in our tests were the price of possible carbon credits and, not surprisingly, the underlying biomass growth curve. In the worst-case scenario, assuming no tree growth after year 12 and all economic factors to take on their most unfavourable values, sequestration costs would about double. In the best-case scenario, in contrast, sequestration costs could decrease by half.Climatologically, using a plantation size of 100 km x 100 km, for simulations with an advanced land-surface-vegetation-atmosphere model, we found a decrease of annual mean temperature over the plantations of the order of 1°K and an occurrence and / or enhancement of precipitation by approximately 11 mm and 30 mm averaged over the plantations during summer time in Oman and the Sonora, respectively. Particularly in Oman, formation of dew was predicted during spring, fall, and winter. Although this paper concentrates on the growth of *Jatropha* in hot, dry areas, the models devised for the agronomic, economic and climatic aspects of this study are sufficiently flexible and transparent that calculations could be made for alternative scenarios provided relevant data were available.

Our *ex ante* assessment had to be based on many data sources and on simulation methods of different degrees of reliability. Particularly lacking were, information on the soil nutrients and water dynamics of *Jatropha curcas*, long term (up to 20 yr) comprehensive data on its growth and data that could lead to a complete life cycle analysis. We would therefore strongly recommend establishing a pilot project using sea-water desalination in order to gather more precise on-field data. This would help us to optimize irrigation, cultivation and carbon monitoring and improve the assessment of possible environmental risks. Reflecting on the urgent need to take action on climate change we strongly recommend including carbon farming in dry coastal areas in the portfolio of mitigation strategies.Overall, we hope that we have demonstrated that carbon farming is a promising mitigation strategy deserving at least as much attention as many of the other geoengineering options, which are currently being discussed. The interdisciplinary combination of simulations presented in this work can be considered as starting point for studying the substainability of carbon farming.

Acknowledgments

We thank Dr. Peter Lawrence and Frau Sabine Nugent of the Institute for Animal Production in the Tropics and Subtropics, University of Hohenheim, for their careful evaluation and for several major revisions of this manuscript. Furthermore, we thank Dr. Kirsten Warrach, Dr. Hans-Stefan Bauer, Dr. Thomas Schwitalla, and M.Sc. Oliver Branch of the Institute of Physics and Meteorology, University of Hohenheim, for their contributions to the set up and simulations of the WRF-NOAH model system.

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Table Captions

Table 1: Dry matter content and calculated carbon content of the twigs, stems and roots of 32 months old *Jatropha curcas* trees from a plantation in the desert of Luxor, Upper Egypt

Table 2: The volume (V_{CO2}) and mass mixing ratios (m_{CO2}) of CO_2, respectively, as well as the derived mass of carbon (m_c) in the atmosphere

Table 3: Configuration of the WRF model

Table 1 Dry matter content and calculated carbon content of the twigs, stems and roots of 32 months old *Jatropha curcas* trees from a plantation in the desert of Luxor, Upper Egypt

Number of trees	Plant height (m)	Kg dry matter per tree				
		Twigs	Stem	Root	Total dry matter	Total carbon
50	3.25 ± 0.6	4.5 ± 2.3	12.4 ± 4.3	4.1 ± 1.6	21.0	10.5

Table 2 The volume mixing ratio of CO_2 in the atmosphere (V_{CO2}), the mass of CO_2 (m_{co2}) and the derived mass of carbon (m_c)

	V_{CO2}, ppm	**m_{CO2}, Gt**	**m_c, Gt**
Preindustrial	280	2182.9	596.4
Present day	385	3001.4	820.1
Annual increase	1.0-2.0	7.8 – 15.6	2.2 – 4.4

Table 3 Configuration of the WRF model

Properties	**Oman**	**Mexico**
Model domain (horizontal)	80 x 80 grid points 18.96°N, 55.88°E - 21.63°N, 58.72°E	75 x 75 grid points (rotated) 30.19°N, 114.89°W - 32.73°N, 111.92°W
Coordinates of *Jatropha curcas* plantations	NE: 20.45 N, 57.98 E SE: 19.7 N, 57.65 E SW: 20.05 N, 56.75 E NW: 20.9 N, 57.22 E	NE: 31.92 N, 112.97 W SE: 31.33 N, 113.25 W SW: 31.9 N, 114.7 W NW: 32.37 N, 114.45 W
Number of vertical layers	45	45
Horizontal resolution	4 km	4 km
Time step	24 s	24 s

Figure Captions

Fig.1: Outline of the carbon farming project. The top of the atmospheric boundary layer is indicated by the blue hyper surface

Fig.2: Scenes from the *Jatropha curcas* plantation at Luxor, Egypt

Fig.3: Two methods for removing salt from seawater

Fig.4: 2D plots of the reduction in albedo caused by *Jatropha curcas* plantations in Oman (upper panel) and Sonora (bottom panel)

Fig.5 Mean difference between IMPACT and CONTROL ABL top in summer over Oman (upper panel) and Sonora (bottom panel)

Fig.6: Predicted differences in precipitation between planted and desert regions in Oman(upper panel) and Sonora (bottom panel) in summer 2007

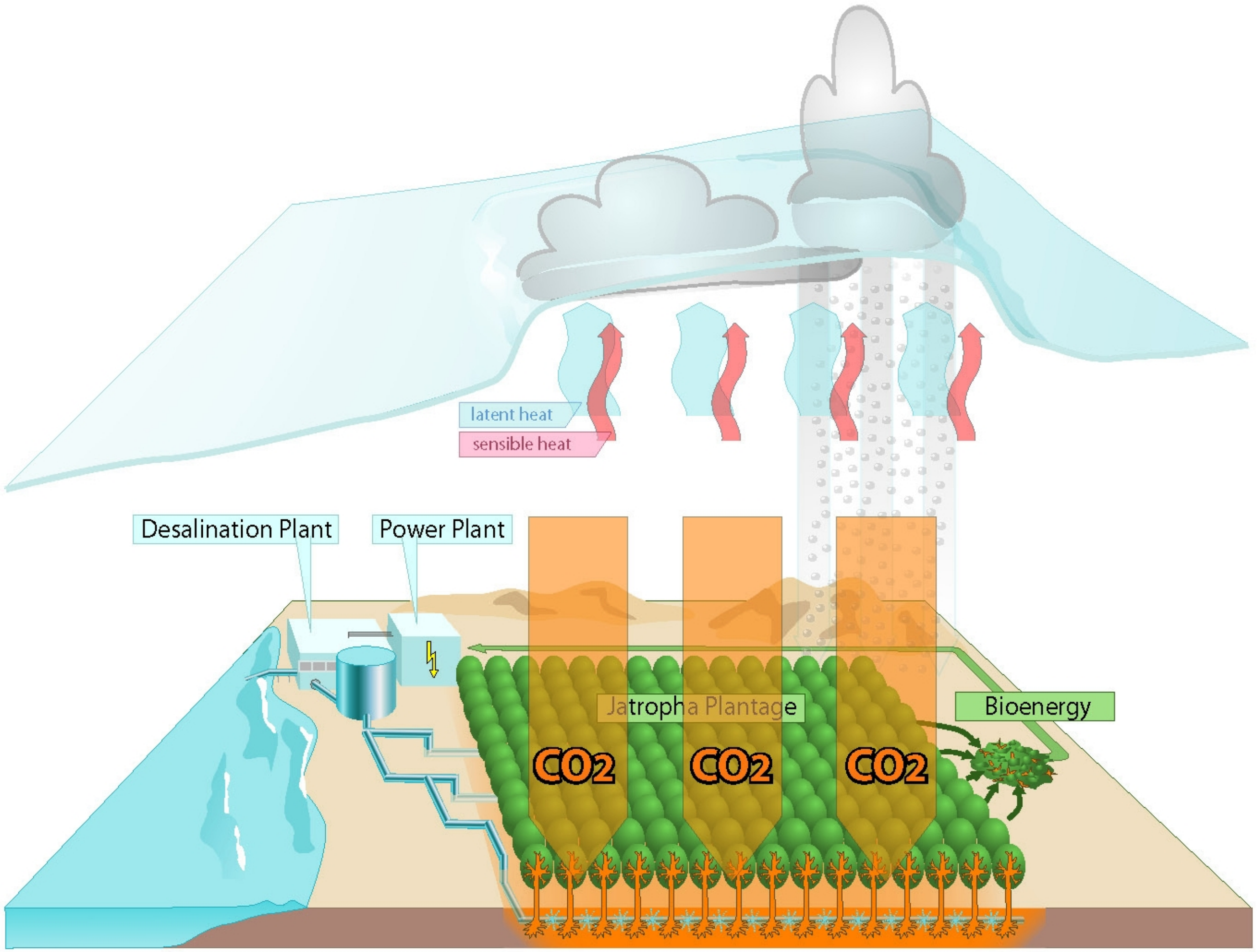


Fig.1 Outline of the carbon farming project. The top of the atmospheric boundary layer (ABL) is indicated by the blue hyper surface

Fig.2 Scenes from the *Jatropha curcas* plantation at Luxor, Egypt

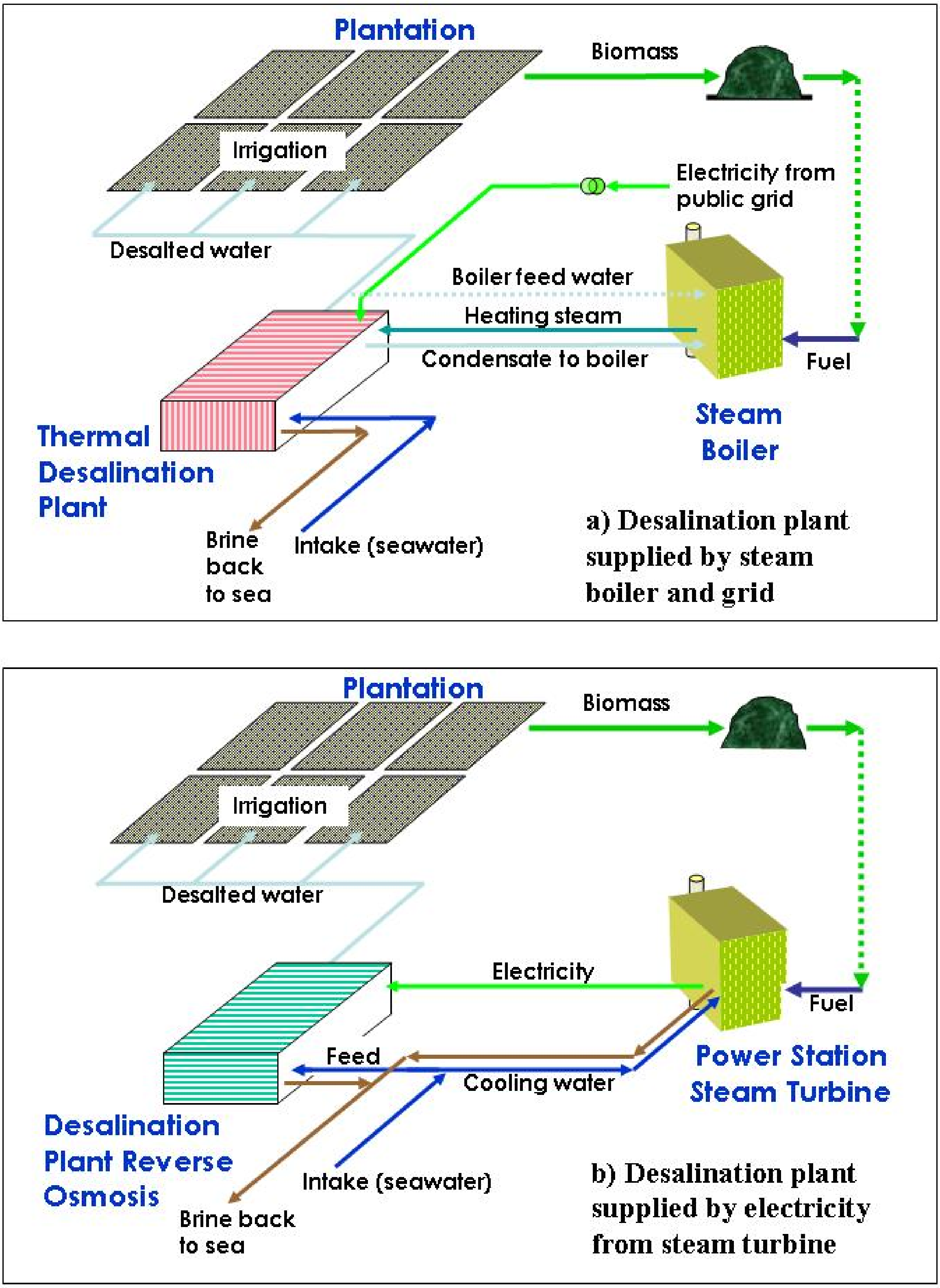
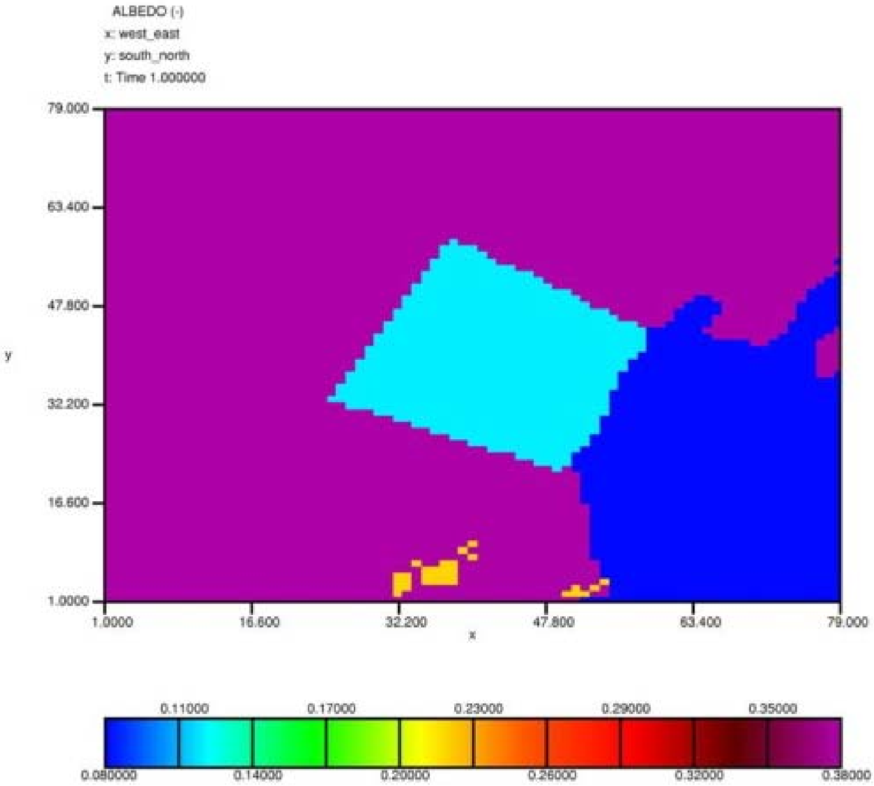


Fig.3 Two methods for removing salt from seawater



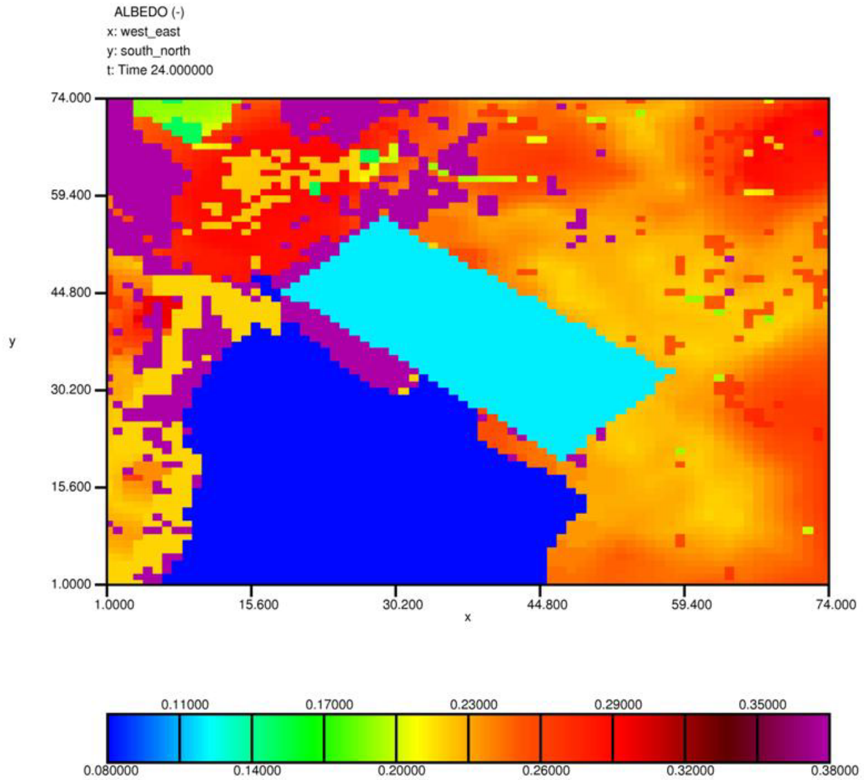


Fig.4 2D plots of the reduction in albedo caused by *Jatropha curcas* plantations in Oman (upper panel) and Sonora (bottom panel)

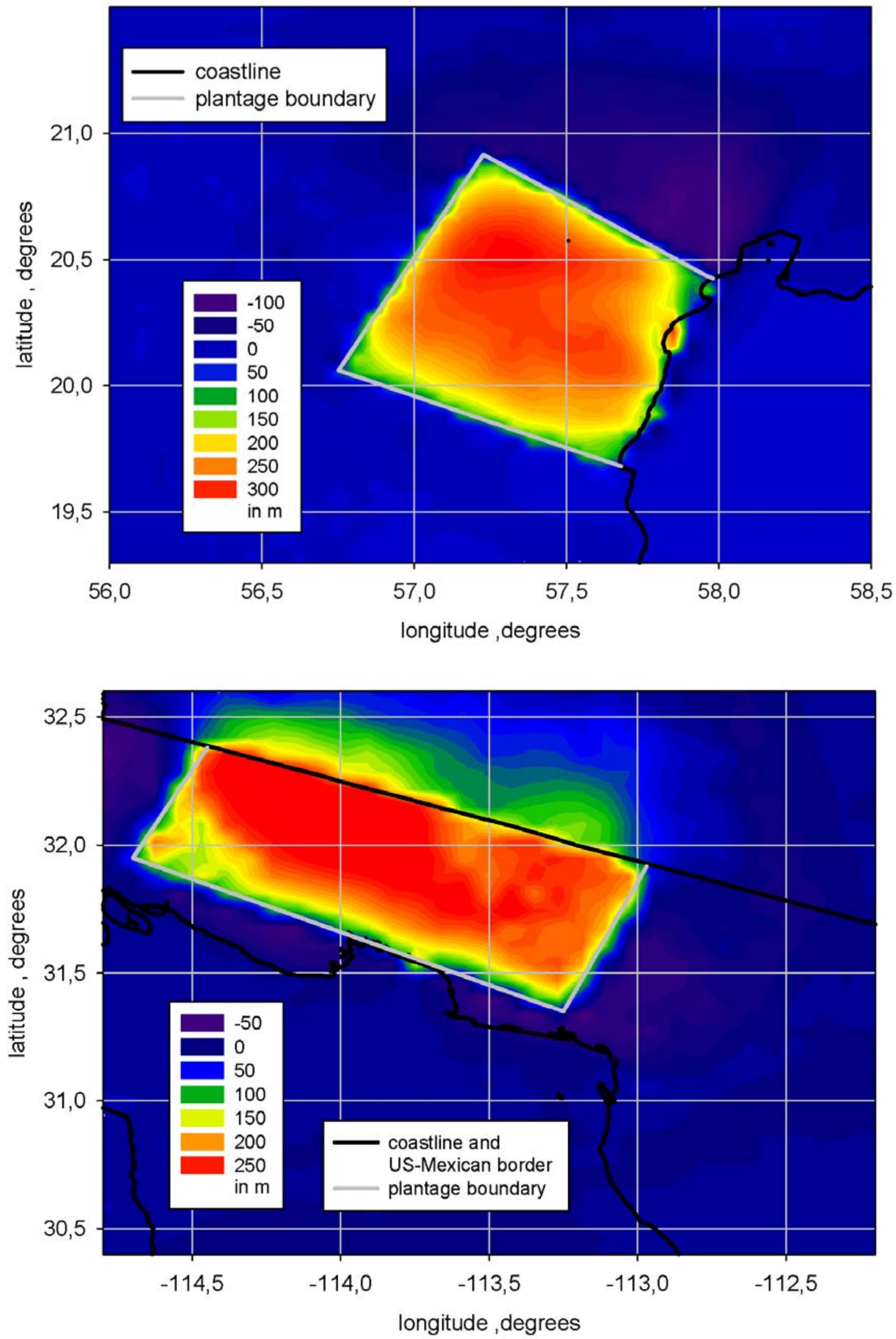


Fig.5 Mean difference between IMPACT and CONTROL ABL top in summer over Oman (upper panel) and Sonora (bottom panel)

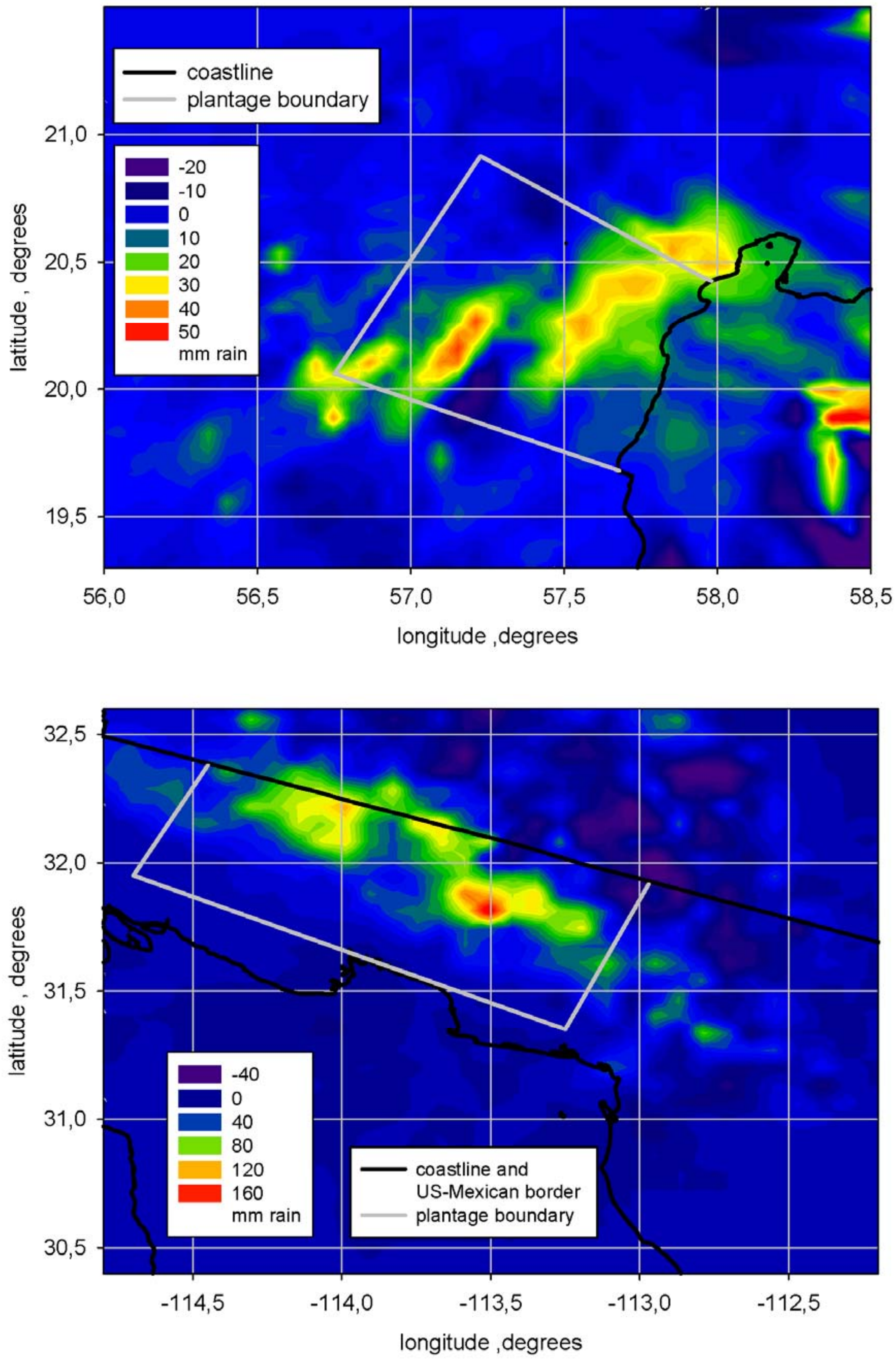


Fig.6 Predicted differences in precipitation between planted and desert regions in Oman (upper panel) and Sonora (bottom panel) in summer 2007