Sequestration of atmospheric carbon dioxide as inorganic carbon under semi-arid forests

Murray Moinester[1], Israel Carmi[2], Joel Kronfeld[2]

[1]School of Physics and Astronomy, Tel Aviv University, 69978 Tel-Aviv, Israel
murray.moinester@gmail.com

[2]Department of Geosciences, Tel Aviv University, 69978 Tel Aviv, Israel
carmiisr@post.tau.ac.il, joel.kronfeld@gmail.com

Extended Abstract, American Meteorological Society's 32nd Conference on Agricultural and Forest Meteorology, 20-24 June, 2016, Salt Lake City, Utah, Session 2: 'Drought Effects on Semi-Arid Ecosystems"

Abstract—Sequestration of carbon through forestation has been proposed to reduce rising atmospheric CO_2 levels. But only organic carbon in the forest has so far been considered. Inorganic carbon storage (carbonate salts) in semi-arid forests, precipitated in the unsaturated zone (USZ), is of greater importance for long term sequestration of global CO_2. Extrapolating data from the Yatir forest in Israel, we suggest that planting trees globally in semi-arid regions has the potential for increasing sequestration of atmospheric carbon dioxide by ~1 billion tons of atmospheric CO_2/year(1 Pg CO_2 yr^{-1}). We stress the need for more accurate estimates, based on future worldwide data, on the rate of such precipitation of inorganic carbon. Still, our present extrapolated estimate represents ~5% of the current rate of increase of 20 billion tons of atmospheric CO_2/year. That is, based on the Yatir data alone, sequestration of atmospheric CO_2 as inorganic carbon under semi-arid forests may represent a sustainable and economic method to help suppress the rate by which CO_2 is increasing in the atmosphere. Semi-arid regions, which comprise ~17% of the global land surface, are generally characterized by marginal agriculture and herding. Low-cost and low-tech afforestation can offer employment in these impoverished regions that are otherwise characterized by few opportunities. The present extended abstract is written as a short opinion piece, without figures and tables, summarizing results from our previously published journal articles.

Key Points:

Forestation in semi-arid regions has the potential to significantly remove atmospheric CO_2 and to sequester it long term in the form of inorganic carbon.

Forestation in semi-arid regions can both reduce atmospheric CO_2 and reduce poverty by providing sustainable employment.

1. Introduction

Since the Industrial Revolution, due to deforestation and land use changes [*Watson, et al.*, 2000], coupled with the burning of massive amounts of fossil fuels, the carbon dioxide concentration in the atmosphere rose from approximately 280 ppmv [*Craig and Keeling*, 1964] to approximately 400 ppmv at the present [ProOxygen, 2015]. More recently, the global atmospheric CO_2 reservoir of ~3130 billion tons has been increasing annually by ~20 billion tons. This increase has occurred predominantly through the burning of fossil fuel and secondarily through the process of deforestation and desertification. Considering the urgency of limiting global warming, ocean acidification and rising sea levels, large climate engineering projects have been proposed to limit global warming by carbon dioxide removal (CDR) and solar radiation management (SRM) [*Linnér and Wibeck (2015)*]. The effectiveness, cost and risk of these and other proposals are currently being investigated, including relying more on nuclear energy worldwide, and some of these will hopefully soon be employed to retard the increasing atmospheric CO_2 concentration. We propose tackling part of the needed reduction in CO_2 concentration by using an economical and sustainable low-tech method to reverse the secondary processes of deforestation, specifically in semi-arid regions.

The burning of fossil fuels is releasing carbon that had been previously taken out of the atmosphere in prior geological eras, particularly during the Carboniferous Period when the great coal and petroleum fields were laid down [*Berner and Kothavala*, 2001; *Rothman*, 2001, 2002; *Bergman et al.*, 2004; *Franks et al.*, 2014]. The CO_2 was stored primarily as a chemically reduced form of plant-based organic material that had been converted to coal or petroleum. These fuels are now being oxidized and the carbon is being returned to the atmosphere as carbon dioxide. Many methods of halting or reducing the increase in atmospheric CO_2 are currently being investigated, including relying more on nuclear energy. One way being considered is to once again utilize plant photosynthesis to abstract atmospheric CO_2 and store it as organic carbon in trees. In effect, photosynthesis drives biological pumps, whereby atmospheric CO_2 entering plant stoma is converted to sugars and polysaccharides, while oxygen is produced as waste. Thus, planting trees has been proposed as being effective in sequestering atmospheric CO_2, both as Above-ground Biomass Carbon (ABC) as well as in the roots [*Johnson and Colburn*, 2010; *Kell*, 2012; *Tans and Wallace*, 1999; *Watson* et al., 2000]. The carbon observed in the above ground plant mass, the leaf litter and organics disseminated in the soils (soil organic matter), comprise organic carbon. Forestation can store large amounts of organic carbon. For example, almost 4 billion tons of ABC has been stored since 2003 by tree planting in northern China. This equals almost 25% of its annual fossil fuel emissions [*Liu et al.*, 2015]. Ancillary benefits also accrue. Among these are soil stabilization, reduced erosion and runoff, improved soil structure and quality, as well as reduced soil biogenic nitric oxide (NO) emissions [*Gelfand et al.*, 2009].

However, all may not be so sanguine, considering that trees have a finite life time. Except for exceptional species, they should be considered as carbon stores in terms of centuries and not millennia. When trees die and decompose, much of the carbon recycles as CO_2. Most forestation efforts have so far been carried out in temperate zones [*Martin et al*, 2001]. But this is where most productive agriculture is carried out. Boyson pointed out [2015] that attaining mandated climate goals via ABC would require cutting food production by converting crop lands to forests. Moreover, large amounts of fertilizer would be required, whose runoff would likely degrade water supplies. Thus, ABC conversion of atmospheric CO_2 to terrestrial biomass may come at an egregious cost. Planting forests in the temperate zone is not the optimum model.

2. **An alternate carbon sequestration model**

2.1 The case for inorganic carbon sequestration in semi-arid regions

Forestation efforts should be directed at semi-arid regions where atmospheric CO_2 is also sequestered as inorganic carbon. These regions have marginal agriculture, but indigenous flora (trees and shrubs with deep roots) can be sustained by the approximately 250-600 mm of annual rainfall. The United Nations Environment Program (UNEP) has adopted an Aridity

Index (AI) as a measure of aridity [Black, 2007]. It is defined as AI = P/PET, the ratio between annual effective precipitation (P) and annual Potential Evapo-Transpiration (PET). The PET measures the atmosphere's ability to remove water from the ground, by plant transpiration and direct evaporation, if the ground were water-saturated. Semi-arid regions have Aridity Index values 0.20 < AI < 0.50, and cover approximately 17.7% of the global terrestrial surface. By contrast, dry sub-humid regions have 0.50 < AI < 0.65, and cover approximately 9.9% of the global terrestrial surface. The **unsaturated zone (USZ)** in semi-arid region is deeper than in temperate regions. The USZ is that zone that extends from the land surface cover downwards into the sediment until the top of the subsurface aquifer (water table). It is the upper effective soil portion of the USZ into which trees respire CO_2 through their roots. The relative effective thicknesses of different USZs can be readily seen by comparing their average maximum rooting depths. For temperate regions, the maximum rooting depths of coniferous and deciduous forests are ~2.8 m. In drier areas, plants must sink roots much deeper to reach water, in order to survive. The roots of the Shepherd's tree (*Boscia albitrunca*) and the Accacia can exceed 60 m in Africa's Kalahari, while the Israeli Tamarisk (*Tamarix aphylla*) can send its roots down 20 m [Canadell *et al.*, 1996]. More significant is the effective process of long term storing of inorganic carbon below the ground surface in the USZ of the semi-arid region. This has generally been neglected, but can be more important than organic carbon storage, when considering carbon sequestration over the long term. The CO_2 that is released through the roots, combined with bacterial oxidation of soil organic matter, can generate soil CO_2 partial pressures that can be orders of magnitude higher than that in the overlying ambient atmosphere [e.g. *Carmi et al.*, 2013; *Clark and Fritz*, 1999; *Pumpanen et al.*, 2008]. Some of this gas diffuses upwards and leaves the soil. The rest can be sequestered. The high partial pressure of CO_2 facilitates the formation of bicarbonate (HCO^-_3) in the soil moisture of the unsaturated zone. Some is generated in the recharge water by formation of carbonic acid ($CO_2(g) + H_2O \rightarrow 2HCO_3$), enhanced by the high partial pressure of CO_2 from the root zone; while some is generated by carbonic acid dissolving calcite ($H_2CO_3 + CaCO_3 \rightarrow Ca^{+2} + 2HCO^-_3$), as well as by oxidation of soil organic matter and silicate weathering. On the other hand, due to evaporation of soil water, bicarbonate (HCO^-_3) precipitates as a secondary soil lime ($CaCO_3$) at varying depths within the USZ. Where rainfall is plentiful, this precipitate dissolves. In semi-arid or arid regions, where rainfall is sparse, precipitated lime can remain stable for thousands of years [*Cerling*, 1984]. The carbonate trapped in the soil, the bicarbonate and CO_2 gas, all together comprise sequestered inorganic carbon. Organic carbon storage has been extensively studied in the Yatir Forest. More recently, we have studied inorganic carbon in the same forest.

2.2 The Yatir Forest Site – a representative semi-arid reforested site

The Yatir Forest (GPS: 31.348051, 35.050801) is situated at an elevation of ~650 m above sea level, along the southwestern flanks of the Judean Hills of Israel, at the edge of Israel's Negev desert. Beginning in 1964, Keren Kayemeth LeIsrael - Jewish National Fund foresters planted four million trees at Yatir. It is now the largest forest in Israel, covering 30,000 hectares [KKL-JNF, 2016]. The topsoil is rather shallow and is composed of imported loess (fine sand-silt-clay wind-blown sediment). The forest comprises mainly of Aleppo pine (Pinus halepensis Mill), with some subordinate cypress and other pine species that were planted in the 1960s. The trees have a mean height of 11 m; and the average depth of the soil cover is

~5 m. The soil cover had been lost as the forests suffered repeated devastation with concomitant soil erosion over the millennia, as had the rest of the country. The history of the soil degradation has been preserved in the isotopic changes noted in radiocarbon dated groundwater [Rogojin *et al.*, 2002]. The understory vegetation is minor. The annual precipitation is approximately ~30 cm, mostly falling during the winter. The depth from the USZ to the underlying groundwater table exceeds 300 m. Despite the present low precipitation, this new forest is productive and stores carbon relatively effectively. Thus, semi-arid regions should not be overlooked in climate studies, considering their significant global surface area and their ability to store carbon in forested biomass and soil [*Grünzweig et al*., 2003; *Grünzweig et al.*, 2007; *Rotenberg and Yakir*, 2010]. The ~2,800 ha Yatir Forest represents a tenth of the Israeli semi-arid region that was reforested over the past century. Koch et *al*. [2000] calculated, using conservative estimates, that such relatively small forests sequester about one percent of Israel's anthropogenic carbon emissions. These results are similar to other studies that show the potential of savannas to act as carbon sinks [*Fisher et al.*, 2014], especially when the grasslands are converted to forests [*Hibbard et al.*, 2001, 2003]. In all of the above cases, only *organic carbon* was considered. The importance of *Inorganic Carbon,* coupled to the unsaturated zone of semi-arid regions, has been only recently been stressed [*Moinester et al.*, 2014; *Godfrey-Smith et al.*, 2015; *Moinester et al.*, 2016].

The Yatir Forest data were obtained in field studies close to the Yatir Bio-Ecological station; and are used here to make carbonate sequestration estimates, to demonstrate the importance of semi-arid USZs. The data included gas and soil samples, from which the gas composition, mineralogical and soil moisture and other parameters were determined [Carmi *et al.,* 2013]. These data, including isotopic analyses, have been published [Carmi *et al*., 2015]. The calcite ($CaCO_3$) precipitation rate was determined from the decrease with depth of Dissolved Inorganic Carbon (2.7% $yr^{-1}L^{-1}$). The samples were collected at the same site over 3 field campaigns from 2006 to 2010 in depth profiles extending from the surface to a depth of almost 4.5 m, and the data was produced from this profile. Depth profiles were converted to time profiles by estimating the downward flow rate (~11 cm y^{-1}) of the water through the USZ using radioactive tritium in the profile as a tracer. The techniques developed and used for sampling the soil moisture and the inorganic carbon for isotopic measurements have been presented in Carmi [2007, 2009].

The values at 2.2 meters, mid-way down the section, are taken as representative of the amount of inorganic carbon precipitate in Yatir [*Carmi et al.,* 2015]. In the absence of other measurements, we take these values as representative of what can be expected elsewhere in the USZs of semi-arid regions globally. We estimate the global effective soil depth of the semi-arid USZ to be 6 m, which may be a conservative value. At another Israeli semi-arid site, Nizzanim, situated along the Coastal Plain, the unsaturated zone extends to 22 m, and plant roots have been encountered at least to half of this depth. The semi-arid North African Sahel region has received a thick extensive eolian sedimentary cover derived from wind-blown sands coming off the Sahara to the north [*Pavelic et al.,* 2012]. Therefore, taking a depth of 6 m for the upper soil layer of the USZ in the following calculations should be considered conservative.

3. Calculating the sequestration potential of inorganic carbon in semi-arid regions

As percolating rainwater passes through the soil, part of the CO_2 in the soil is converted to HCO^-_3 bicarbonate. Some of this bicarbonate precipitates within the unsaturated zone (USZ) as secondary lime. This happens when soil moisture charged with bicarbonate evaporates, after which there is insufficient water to keep the bicarbonate in solution. Measurements of porosity, humidity, and dry sediment density of representative Yatir sediment at 2.2 meters depth give the result that one liter of sediment comprises 0.47 L solid + 0.12 L water + 0.41 L gas. In 1 L of sediment, the amount of **dissolved inorganic carbon (DIC)** is 5.64 mmole, and the calcium carbonate (lime) precipitation rate is 2.7% yr^{-1}, corresponding to 0.15 mmole yr^{-1} (0.027 yr^{-1} x 5.64 mmole) [Carmi *et al.,* 2015]. These data correspond to 1.83 mg carbon yr^{-1} (0.153 x 12 = 1.84 mg yr^{-1}), equivalent per liter of sediment to 6.71 mg CO_2 yr^{-1} L^{-1} removed from the atmosphere.

Consider now a USZ volume of 1 km^2 and 6 m depth (~6x109 L) with growing trees or deep rooted shrubs on top and roots in the USZ (source of CO_2). The lime precipitation within this volume of sediment is approximately 40.3 tons of CO_2 per year (6.71 x 10^{-3} g yr^{-1} L^{-1} x $6x10^9$ L= 40.3 x 10^6 g = 40.3 ton).

To make a *"gedanken"* estimate, assume that the topsoil composition and depth and lime precipitation rate in Yatir is representative of the global semi-arid area (~23 x 10^6 km^2), following forestation. With these assumptions, roughly 1 billion tons of CO_2 (40.3 x 10^6 g km^{-2} x 23 x 10^6 km^2 = 0.927 ~ 1.0 Pg) could potentially be precipitated globally each year in the USZ as lime, following forestation. Uncertainties are not shown for this estimate, since we do not know how representative Yatir is of the global semi-arid area. Forestation related lime precipitation data in the USZ of other semi-arid regions are not yet available.

A value of 1 billion tons yr^{-1} of CO_2 removed from the atmosphere represents a significant ~5% of the present increase of 20 billion tons yr^{-1} of CO_2 in the atmosphere. Tentatively, based on the Yatir data, sequestration of atmospheric CO_2 as inorganic carbon under semi-arid forests represents a sustainable and economic method to help suppress the rate by which CO_2 is increasing in the atmosphere. Our estimates should be corroborated and refined by extending the Yatir studies to other semi-arid regions.

4. Considerations for the global carbon budget

The carbon global mass balance is not fully constrained [*Schlesinger*, 2000; *Houghton*, 2007; *Ballantye*, et al., 2012; *Evans et al.*, 2014], for there appears to be a terrestrial sink that is lacking. Recently, *Li et al.* [2015] noted that DIC stored within old saline/alkaline groundwater beneath desert regions may contribute to constraining the carbon budget. This suggestion is consistent with our previous estimates [*Moinester et al.*, 2014; *Godfrey-Smith et al.*, 2015]; though we considered two factors in the quantification of the estimated missing terrestrial sink: inorganic carbon storage precipitated in the unsaturated zone (USZ), as well as DIC in global aquifers.

5. Reforestation of the global semi-arid areas to store atmospheric carbon dioxide

The calculations given here are only very rough estimates, based on the rate of precipitation of carbonate in the USZ at Yatir: 2.7 % yr^{-1}. More accurate estimates can be made once more data are obtained globally on the rate of precipitation of calcium carbonate from the DIC in USZ sediments. Such estimates will include data from other Israeli sites; for example, the Nizzanim nature reserve [Carmi et al, 2009]. However, our *"gedanken"* estimate here already suggest a significant potential to achieve long term sequestering of inorganic carbon.

Based on this estimate, a particular land management may be suggested - widespread tree planting in semi-arid regions. However, such a recommendation requires strong proof of concept and analysis of potential unintended consequences, perhaps most notably on energy and water fluxes and biodiversity. On these subjects, the Yatir forest in fact shows that the consequences were completely positive [KKL-JNF, 2016]. If data from other semi-arid forests support the Yatir results, such a global land management policy should definitely be undertaken.

To date, the semi-arid regions are not industrialized, and are too dependent on rainfall to offer more than employment in only marginally profitable agriculture or herding. Persistent poverty may be a focus for political or social instability. Afforestation and reforestation however can provide long term sustainable employment to such populations at less initial and continuing running costs than required for major engineering endeavors for fulfilling climate goals. Moreover, the planting of trees will also have positive climate cooling effects and prevent encroaching desertification. Besides, over the years, the above ground biomass carbon (organic carbon) can be harvested to supply such commodities as lumber and charcoal. This is not merely speculation. Newly independent Israel suffered similar problems. Reforestation efforts were carried out initially to provide employment as a stop gap effort, until factories and suitable jobs could be established. The social fabric of the country was helped by planting forests in a country of limited natural resources, before the global climate aspect was a consideration. The forests today are esthetic, counter encroaching desertification, and provide wild life habitat and recreational facilities. Other semi-arid economically distressed regions, such as the Sahel, where the sediment is also loess, should be similarly forested; but on a large scale with international assistance at first. In this case, the primary aim would be carbon dioxide sequestration in the form of inorganic carbon.

References

Arora, V.K. (2002), The use of the aridity index to asses climate change effect on annual runoff, *Journal of Hydrology*, 265 (1), 164-277.

Black, P. E. (2007), Revisiting the Thornthwaite and Mather Water Balance. JAWRA Journal of the American Water Resources Association, 43: 1604–1605. doi: 10.1111/j.1752-1688.2007.00132.x

Boysen, L. (2015), Low climate potentials but large side-effects of terrestrial CO_2 removal-Insights from quantitative model assessments, paper presented at
Climate Engineering Research: Current State and Future Perspectives Symposium, Berlin-

Brandenburg Academy of Sciences and Humanities, July 7-10, 2015, Berlin, Germany. http://www.spp-climate-engineering.de/the-symposium.html

Ballantye, A. P., C.B. Alden, J.B. Miller, P.P. Tan and J.W. White (2012), Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years, *Nature*, 488, 70-72.

Bergman, M., T.M. Lenton and A.J. Watson (2004), COPSE: a new model of biogeochemical cycling over Phanerozoic time, *Am. J. Sci.*, 304, 397-437.

Berner, R.A. and Z. Kothavala (2001), GEOCARB III: A revised model of atmospheric CO_2 over Phanerozoic time, *Am. J. Sci.*, 301, 182-204.

Canadell, J. and R.B. Jackson, J.R. Ehleringer , H.A. Mooney, O.E. Sala and E.D. Schulze (1996), Maximum rooting depth of vegetation types at the global scale, *Oecologia*, 108, 583-595.

Carmi, I. (2007), Processes that affect the isotopic concentration of carbon in the unsaturated zone: implications for improved dating of groundwater with ^{14}C, Ph.D. thesis, Tel Aviv University, Israel.

Carmi, I., J. Kronfeld, Y. Yechieli, D. Yakir, E. Boaretto and M. Stiller (2009), Carbon isotopes in pore water of the unsaturated zone and their relevance for initial ^{14}C activity in groundwater in the coastal aquifer of Israel, *Chem. Geol.,* 268, 189-196.

Carmi, I., D. Yakir, J. Kronfeld and M. Stiller (2013), Variations in soil CO_2 concentrations and isotopic values in a semi-arid region due to biotic and abiotic processes in the unsaturated zone, *Radiocarbon* 55, 932-942.

Carmi., I, D. Yakir, Y. Yechieli, J. Kronfeld and M. Stiller (2015) Variations in the isotopic composition of dissolved inorganic carbon in the unsaturated zone of a semi-arid region, *Radiocarbon*, 57, 1-10.

Cerling, T.E. (1984), the stable isotopic composition of modern soil carbonate and its relationship to climate, *Earth Planet. Sci. Lett.*, 72, 229-240.

Clark, I. and P. Fritz (1999), *Environmental Isotopes in Hydrology*, 2nd Edition, Lewis Publishers, Boca Raton, 328pp.

Craig, H. and C.D. Keeling (1963), the effects of atmospheric NO_2 on the measured isotopic composition of the atmospheric CO2, *Geochim. Cosmochim. Acta*, 27, 549-551.

Evans R.D, A. Koyama, D.L. Sonderegger, T.N. Charlet, B.A. Newingham, L.F. Fenstermaker, B. Harkow, V.J. Jin, K. Ogle, S.D. Smith and R.S. Nowak (2014), Great ecosystem carbon in the Mojave Desert after ten years exposure to elevated CO_2, *Nat. Clim. Change*, 4, 394-397, doi:10.1038/nclimate 2184.

Fisher, N.J., I.M. Rao, M.A. Ayarza, C.E. Lascano, J.J. Sanz, R.J. Thomas and R.R. Vera (1994), Carbon storage by introduced deep rooted grasses in the South American savannas, *Nature*, 371, 236-238.

Franks, P.J., D.L. Royer, D.J. Beeling ,P.K. Van de Water, D.J. Cantrill, M.M. Barbour and J.A. Berry (2014), New constraints on atmospheric CO_2 concentration for the Phanerozoic, *Geophys. Res. Lett.*, 41, 4685-4694.

Gelfand, I., G. Feig, F.X. Meixner and D. Yakir (2009), Afforestation of semi-arid shrub land reduces NO emission from soil , *Soil Biol. Biochem.*, 41, 1561- 1570.

Godfrey-Smith, D., M. Moinester, I. Carmi and J. Kronfeld (2015), Sequestration of Atmospheric Carbon in Semi-Arid Regions as Inorganic Carbon, Poster presented at Climate Engineering Research: Current State and Future Perspectives Symposium, Berlin-Brandenburg Academy of Sciences and Humanities, July 7-10, 2015, http://www.spp-climate-engineering.de/the-symposium.html, http://www-nuclear.tau.ac.il/~murraym/MoinesterForestation2.pdf

Grünzweig, J.M., I. Gelfand, Y. Fried and D. Yakir (2007), Biochemical factors contributing to enhanced carbon storage following afforestation of semi-arid shrub land, *Biogeosciences* , 4, 891-904.

Grünzweig , J.M.,T. Lin, E. Rothenberg, A. Schwarz and D. Yakir (2003), Carbon sequestration in arid-land forest, *Global Change Biol.*, 9, 791-799.

Hibbard , K.A., S. Archer, D.S. Schimel and D.W. Valentine (2001), Biogeochemical changes accompanying woody plant encroachment in a subtropical savanna, *Ecology*, 82, 1991-2011.

Hibbard , K.A., D.S. Schimel, S. Archer, et al. (2003), Grassland to woodland transitions: Integrating changes in landscape structure and biochemistry, *Ecol. Appl.*, 13, 911-926.

Houghton, T.A. (2007), Balancing the global climate budget, *Annu. Rev. Earth Planet. Sci.*, 313-347.

Johnson, I. and R. Coburn (2010), Trees for carbon sequestration, *Primefact*, 981, 1-6, http://www.forestrycorporation.com.au/__data/assets/pdf_file/0006/438234/Trees-for-carbon-sequestration.pdf

Kell, D.B. (2012), Large scale sequestration of atmospheric carbon via plant roots in natural and agricultural ecosystems: why and how. *Philosophical Transactions of the Royal Society B: Biological Sciences*, B367,1589-1597.

KKL-JNF (2016), http://www.kkl.org.il/eng/tourism-and-recreation/forests-and-parks/yatir-forest.aspx

Koch, J., U. Dayan and A. Mey-Marom (2000), Inventory of Emissions and removals of greenhouse gases in Israel, *Water Air Soil Pollut*., 123, 259-271.

Li, Y., Y-G. Wang and L-S. Tang (2015), Hidden carbon sink beneath desert, *Geophys. Res. Lett*., *42*(14), 5880-5887.

Linnér, B. O., and Wibeck, V. (2015), Dual high-stake emerging technologies: a review of the climate engineering research literature. *Wiley Interdisciplinary Reviews: Climate Change*, *6*, 255-268.

Liu, Yi Y., A.I. J. M. van Dijk, R.A. M. de Jeu, et al. (2015), Recent reversal in loss of global terrestrial biomass, *Nat. Clim. Change*, doi: 10.1038/nclimate2581.

Martin, P. H., G. J. Nabuurs, M. Aubinet, T. Karjalainen, E. L. Vine, J. Kinsman and L. S. Heath (2001), Carbon sinks in temperate forests*, Annu. Rev. Energy Environ., 26*, 435-465.

Moinester, M., I. Carmi and J. Kronfeld (2014), Sequestration of inorganic carbon via forestation, Poster presented at the Climate Engineering Conference, 18-21 August, Berlin, Germany, http://www.ce-conference.org,
http://www-nuclear.tau.ac.il/~murraym/MoinesterForestation.pdf

Moinester, M., Kronfeld, J., and Carmi, I. (2016), Sequestration of Atmospheric Carbon Dioxide as Inorganic Carbon in the Unsaturated Zone of Semi-Arid Forests, Abstract submitted to 32nd Conference on Agricultural and Forest Meteorology, 20-24 June 2016, Salt Lake City, Utah, https://www2.ametsoc.org/ams/index.cfm/meetings-events/ams-meetings/32nd-conference-on-agricultural-and-forest-meteorology/call-for-papers/

Pavelic, P., M. Giordano, B. Keraita, V. Ramesh and T. Rao (2012), Groundwater availability and use in Sub-Saharan Africa. A review of 15 countries. Colombo, Sri Lanka: International Water Management Institute (IWMI), 276pp., doi:10.5337/2012.213.

ProOxygen(2015), http://www.co2.earth

Pumpanen, J., H. Ilvesniemi, L. Kulmala, E. Siivola, H. Laakso, P. Kolari, C. Helenelund, M. Laakso, M. Uusimaa and P. Hari (2008), Respiration in Boreal forest soil as determined from carbon dioxide concentration profile*, Soil Sci. Soc. Am. J., 72*, 1187-1196.

Rogojin, V., I. Carmi, J. Kronfeld and A.S. Talma (2002), A better developed soil profile during Biblical Times in the western Galilee: ^{15}N evidence in ^{14}C dated groundwater, *Geochronometria*, 21, 79-84.

Rothman, D.H. (2001), Global biodiversity and the ancient carbon cycle, *Proc. Natl. Acad. Sci.*, 98, 4305-4310.

Rothman, D.H. (2002), Atmospheric carbon dioxide levels for the last 500 million years, *Proc. Natl. Acad. Sci.*, 99, 4167-4171.

Rotenberg, E. and D. Yakir (2011), Distinct patterns of change in surface energy budget associated with forestation in the semi-arid region, *Global Change Biol.*, 17, 1536-1548.

Schlesinger, W.H. (2000), Carbon sequestration in soils, *Science*, 284, 2095.

Tans, P.P. and D.W.R. Wallace (1999), Carbon cycle research after Kyoto, *Tellus*, 51B, 562-571.

Watson, A.T., I.R. Nobel, B. Bolin, et al. (Eds.) (2000), *Land Use, Land-Use Change, and Forestry,* Cambridge University Press, Cambridge, UK.