POTENTIAL GLOBAL SEQUESTRATION OF ATMOSPHERIC CARBON DIOXIDE BY SEMI-ARID FORESTATION

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ABSTRACT: The global carbon sequestration potential of semi-arid forests is described. Organic and inorganic carbon sequestration was studied in Israel’s planted Yatir forest, a 28 km² Aleppo pine forest growing at the semi-arid timberline (with no irrigation or fertilization). The organic carbon sequestration rate (above and below ground) was measured as 550 g CO₂ m⁻² yr⁻¹, by Eddy Covariance flux and Carbon Stock counting methods. Assuming that the soil composition at Yatir is representative, we estimate a global organic sequestration rate of roughly 3.0 billion tons CO₂ yr⁻¹, after future global forestation, by extrapolating to 20 % of the global semi-arid area. Consider now also the inorganic carbon sequestration rate. A tree’s roots exhale CO₂ into the soil after some of the tree’s glucose (produced by photosynthesis) has been oxidized to supply energy for the tree’s cellular processes. We quantify the annual inorganic sequestration rate in Yatir soil cores by measuring the decreased density (due to calcite precipitation) versus depth, of bicarbonates in the liquid phase of the soil’s unsaturated zone (USZ). We found that the bicarbonate concentration decreases with depth, as the bicarbonates precipitate and are incorporated within the USZ. The depth profiles were converted to time profiles, taking into account that the annual rate of downward water percolation at Yatir has been measured to be ~11 cm yr⁻¹. At Yatir, in 1 Liter of sediment, the calcite precipitation rate was measured as 22 mg CO₂ yr⁻¹ L⁻¹. The precipitated calcite remains in place long term, not dissolving in low rainfall semi-arid regions. Taking 6 m as the global average depth of root respiration in semi-arid regions, extrapolating as above, roughly 0.8 billion tons of CO₂ could potentially be precipitated globally each year in the USZ as calcite. The total organic plus inorganic sequestration rate of ~4 billion tons CO₂ yr⁻¹ then represents roughly 20 % of the present annual increase of 20 billion tons of CO₂ being added to the present global atmospheric CO₂ reservoir of ~3200 billion tons. Although the uncertainties are high, this estimate already demonstrates the global potential, the need for further measurements, and the need to begin implementing a global land management policy of widespread tree planting in semi-arid regions.

KEYWORDS: global carbon sequestration; organic and inorganic carbon; semi-arid forest

STATEMENTS AND DECLARATIONS: The authors declare that they have no conflict of interest.
Part of this work was supported by Weizmann Institute of Science during R. Qubaja’s PhD in D. Yakir’s Lab of Ecophysiology.

DATA AVAILABILITY: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.
1. INTRODUCTION

Carbon dioxide is currently being emitted globally at roughly 40 billion tons per year (40 Gt CO₂ yr⁻¹). About 44 % of CO₂ emissions accumulate in the atmosphere, 26 % in the ocean, and 30 % on land (ProOxygen 2022). Since the Industrial Revolution, the CO₂ concentration in the atmosphere has risen from approximately 280 ppmv to approximately 420 ppmv at present (ProOxygen 2022). The global atmospheric CO₂ reservoir of ~3200 billion tons is presently increasing annually by ~20 billion tons. This increase is occurring in part through the burning of fossil fuels and deforestation. The increase is considered a potential cause of increased ocean acidification and global warming, with attendant glacial retreat coupled to sea level rise (Farquharson et al. 2019). Reducing greenhouse gas emissions is necessary; otherwise, global sea level rise and ocean acidification and global warming would seriously disrupt the modern world order. Indeed, the COP26 Glasgow Climate Pact acknowledges that CO₂ emissions must fall by 45 % from 2010 levels by 2030 for global warming to not rise more than 1.5 °C above pre-industrial levels. Very expensive, large climate engineering projects have been proposed by carbon dioxide removal (CDR) and solar radiation management (SRM) (Linnér and Wibeck 2015).

Here, we consider complementary forestry methods, which are lower cost and simpler to employ, and could be carried out in drylands (Bastin et al., 2019; Heck et al. 2018; Johnson and Coburn 2010; Kell 2012; Liu 2022; Moinester et al. 2014, 2016; Potapov et al., 2011; Rohatyn et al. 2021; Rotenberg et al. 2021; Watson et al. 2000; Zhang et al. 2013). Most forestation efforts have so far been carried out in temperate zones (Martin et al. 2001). However, this is where most productive agriculture is carried out. Boysen et al. (2017) and Ostberg et al. (2018) pointed out that attaining mandated climate goals via forestation would overtly reduce arable lands available for food production. Moreover, large amounts of fertilizer would be required; whose runoff would likely degrade water supplies. Thus, such a program in temperate zones may come at an egregious cost. Planting forests in the temperate zone should thus not be considered the optimum model. Therefore, we have studied the efficacy of carrying out such a forestation program in an area of marginal agricultural potential, the semi-arid zone. This zone is important for its significant area, ~18% of the global land surface, ~27 million km². It can readily store organic and inorganic carbon in forested biomass and soil (Grünzweig et al. 2003, 2007; Moinester et al. 2014, 2016; Rotenberg and Yakir 2010; Zhang et al. 2013).

2. YATIR FOREST

Organic and inorganic carbon sequestration were studied in Israel’s planted Yatir forest, a 28 km² Aleppo pine forest growing at the semi-arid timberline (with no irrigation or fertilization) (KKL-JNF 2022). The Jewish National Fund (Keren Kayemeth LeIsrael) foresters have planted ~4 million trees at Yatir. This site (GPS: 31°20′ N, 35°03′ E) is situated above the carbonate Mountain Aquifer (also called the Judea Group Aquifer) at an elevation of ~650 m above sea level, along the southwestern flanks of the Judean Hills, at the edge of Israel’s Negev desert. It is the largest forest in Israel (KKL-JNF 2022).

The Yatir inorganic carbon sequestration data include gas and soil samples, from which the gas composition, mineralogy, soil moisture and other parameters were determined (Carmi et al. 2013). The samples were collected in depth profiles extending from the surface to a depth of almost 4.5 m. The mean annual precipitation is approximately ~285 mm, falling during the winter as high intensity rain events. The rate of downward rainwater infiltration at Yatir was previously determined as ~11 cm yr⁻¹ by tritium radioactivity measurements of the HTO component of soil water extracted from a
sediment profile (Carmi et al. 2015). This downward flow rate was determined by a least square fit to the measurements at different depths, with an uncertainty of about 20 %. This rate is slow compared to the ~45 cm yr\(^{-1}\) infiltration rate into the semi-arid USZ above Israel’s coastal aquifer, which is composed of highly porous beach sands (e.g., Carmi et al. 2018). By way of comparison, Scanlon et al. (2006) estimate that the long-term global average infiltration rate for semi-arid regions is typically below 3.5 cm yr\(^{-1}\), although local extreme variability can exist.

Despite the present low precipitation, the Yatir forest is productive and stores carbon organic relatively effectively without irrigation (Grünzweig et al. 2003). Conditions there are at the drier and hotter edge (Aridity Index AI = 0.18) compared to the world’s semi-arid region (AI = 0.2-0.5) (Arora 2002). The mean annual potential evapotranspiration and precipitation are 1,600 mm and 285 mm, respectively, the evapotranspiration to precipitation ratio is hydrologically balanced (0.94-1.07), with negligible runoff and with an inaccessible groundwater table at greater than 300 m depth. Precipitation is restricted to the winter (December–April), while the remainder of the year is hot and dry (Qubaja et al. 2020A, 2021). We assume in what follows that Yatir is representative of global semi-arid areas.

3. SOIL ORGANIC CARBON (SOC) SEQUESTRATION OF ATMOSPHERIC CO\(_2\)

Organic carbon sequestration is based on utilizing plant photosynthesis to abstract atmospheric CO\(_2\), and then storing it as organic carbon in trees. Photosynthesis during daylight drives biological pumps, whereby atmospheric CO\(_2\) entering leaf stomata combine with H\(_2\)O to produce organic carbon glucose (C\(_6\)H\(_{12}\)O\(_6\)) as well as O\(_2\) oxygen, a very essential byproduct. This photosynthetic process can be represented by the following equation:

\[
6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2
\]  

(1)

The reverse reaction, either by direct burning or involving catalytic reactions, releases the stored CO\(_2\) either directly to the atmosphere or into the soil profile:

\[
C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O
\]  

(2)

The organic carbon residence time for this sequestration (Eq. 1) is over 100 years, considering the typical life span of Aleppo pines and their decomposition time after falling. Thus, extensive forestation 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 Coburn 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, comprise soil organic carbon (SOC). Trees are massive, both in their above and below ground structures, comprising almost 50 % carbon. In addition, the tree litter adds substantial SOC. The below ground mass can be almost as massive via their extensive root structure. In addition to sequestering carbon, semi-arid forests provide important ancillary environmental functions. These include preventing encroaching desertification, producing oxygen, increasing precipitation (Yosef et al. 2018), reducing ocean acidification, improving soil structure and quality and soil stability, reducing erosion and runoff, reducing soil biogenic nitric oxide emissions, reducing air particulate pollution, providing lumber and charcoal, providing wildlife habitat and recreational facilities, providing forest management employment to local populations, and producing carbon offset credits to be sold on global carbon trade exchanges.

Israel’s rainfall is restricted to a short winter rainy season. Since parts of Israel lie within a semi-arid climatic zone, Yatir data may be taken as representative of sequestration processes germane to this zone. Relying upon computer modeling, Yosef et al. (2018) recently noted that despite some potential negative climate feedback effects, forestation should lead to enhanced precipitation and a greater organic carbon sequestration. Qubaja et al. (2020B, 2020C) estimate that such large-scale
forestation may significantly reduce the present ~20 billion ton yr\(^{-1}\) global rate of increase of atmospheric CO\(_2\). Specifically, for Israel’s Yatir Forest, using the data of a 15 year long monitoring program that combined eddy covariance (EC) flux measurements as well as C and N stock counting inventories, an organic carbon sequestration rate above and below ground of 150 grams per square meter per year, corresponding to 550 g organic CO\(_2\) m\(^2\) yr\(^{-1}\), was estimated. The EC method is a key atmospheric measurement technique employed to determine net vertical turbulent fluxes within atmospheric boundary layers. It provided half-hourly based estimates of net ecosystem exchange of CO\(_2\), water vapor, heat, etc. The method provides information on the net fluxes, while the component fluxes of uptake and emission are estimated indirectly by post-processing. Uncertainties (~20 %) were assessed by comparing stock-based and flux-based approaches (Qubaja et al. 2020B). Ecosystem-scale accounts of carbon stocks (CS) were estimated in permanent study plots involving tree size parameters and soil organic carbon (SOC), which are converted to CS with allometric equations and soil sample analyses (Parresol 1999; West et al. 1997). This stock-based approach is generally performed on a few replicated individuals or small plots that need to be scaled up. The original forest inventory assessment was performed in 2001 (Grünzweig et al. 2007) and was repeated 15 years later (Qubaja et al. 2020B) on the same five 30 × 30 m plots in the central part of the forest. A detailed recent forest inventory included estimates of the four main components: standing biomass, litter, soil, and removal (mortality, thinning, and sanitation). The mean annual net ecosystem productivity based on CS over the 15-year observation period depended on the measured increases in C in soil or tree CS over the observation period. The organic carbon residence time is over 100 years, considering the typical life span of Aleppo pines and their subsequent decomposition rate.

Note however that the expected global cooling effect by atmospheric CO\(_2\) reduction may be partially offset by the expected warming effect associated with forestation’s change in land surface albedo (Rohatyn et al. 2021; Zhang et al. 2022; Zhu et al. 2022). Specifically, the reflection of solar radiation incident on a dark forest would be reduced with respect to reflection from light colored soil. The balance is highly dependent on the local soil brightness properties, on local vegetation type prior to forestation, as well as the terrain (slope and direction with respect to the sun), and forest structure and species composition (forest density, leaf area index, diameter at breast height, forest canopy height, tree cover, fraction of young forest, broadleaved versus coniferous trees, e.g., Alibakhshi et al. 2022; Lu et al. 2021; Zhang et al. 2022).

Interestingly, Yosef et al. (2018) and Qubaja et al. (2020B) concluded that organic carbon sequestration from forestation would negate such biogeophysical warming within roughly 6 years. Their estimate was made without considering the added inorganic carbon sequestration that would accompany forestation. Note in addition that a climate figure of merit should relate not only to global warming, but also to reducing the increase in ocean acidification and other problems associated with increasing atmospheric CO\(_2\).

Besides, forests’ surface energy balance and hydrological cycle depend on their land-atmosphere interactions, driven by the interplay of latent heat fluxes (predominately evaporative with phase change) and sensible heat fluxes (predominantly solar heating without phase change). As characterized by their lower Bowen ratios, forests compared to grasslands usually have a greater latent heat flux relative to sensible heat flux (Pielke et al. 2011). This is a consequence of their deeper rooting, greater transpiring leaf area, and increased roughness. Semi-arid forestation thus has the potential to decrease surface temperature through the increase of evapor/transpiration. Besides evaporative cooling, the increased evaporation would increase albedo due to increased low elevation cloudiness. Irrigation of forests can also lead to areas of high latent heat flux relative to sensible heat flux (e.g. Boucher et al 2004, Lobell et al 2006, 2009). The cumulative effects of global semi-arid forests could then tend to contribute to lowering global surface temperatures. Clearly, the global
climate effects of increased latent heating and water vapor and the albedo effect due to semiarid forestation require further study.

With regard to the need for sufficient water supply to carry out forestation in areas of limited rainfall, Liu et al. (2022) propose “comprehensive vegetation carrying capacity” as a guideline/requirement for planning semi-arid forestation. They explain that vegetation should meet three requirements: vegetation stability, hydrological function, and ecosystem services for humans. Thereby, the planted forest would simultaneously avoid ecological, hydrological, and socioeconomic drought (Stenzel et al. 2021). Their concern is that a forest could amplify water consumption through a nonlinear increase in evapotranspiration, depending on tree species, age, and structure, and that this will be further intensified by future global warming. Cao et al. (2010) and Jin et al. (2014) describe this problem with reference to semi-arid forestation projects in China. They explain that when precipitation is lower than potential evaporation, surface soil moisture may not sustain forestation. It is important to note however that rainfall deficient areas often overlie large groundwater reserves of fossil water (aquifers often non-related to the present hydrological regime) that can be exploited (Kronfeld et al. 1993). This would allow forestation projects to proceed forthwith based on the relatively low cost of drilling water wells. Since such aquifers do not benefit from continuous recharge, for the very long term, recharge would be required, for example by complimentary desalination projects.

Grazing in the forest (Yatir for example) is one of the methods for reducing the risk of forest fires, since it reduces the brush biomass, which serves as fuel for fires, and consequently assists in preventing fires from starting and from spreading. Besides, grazing increases surface albedo by exposing more of the original land surface. Semi-arid forests should therefore allow grazing (KKL, 2022).

Research in Israel (KKL, 2022) has shown that the Athel tamarisk, also known as the saltcedar, is a suitable tree for preventing fires from spreading. Trees with low flammability rates and slow consumption rates should therefore be planted, to reduce the probability of fire ignition and diffusion in places at a high risk for fires, and to plant along determined firebreak lines.

Rohatyn et al. (2022) recently estimated that only ~6% of semi-arid and dry sub-humid land areas were potentially afforestable. The excluded areas were mainly cropland (17%), shrubland and forested areas with woody-vegetation having more than 15% coverage (25%), and land (AI < 0.2) incompatible with tree survival (47%). They further estimated that such dryland forestation would not achieve significant global cooling; considering that forest carbon sequestration (cooling) would be offset by the decrease in forest land surface albedo (warming). Their conclusion however did not take into account the preceding discussion, which suggests that considerably more than ~6% of the global semi-arid area would be potentially forestable. In fact, the alternative forestation scenarios of Potapov et al. (20) and Bastin et al. (3) covered 15 and 25% of total drylands, respectively. Assuming that the soil composition at Yatir is representative, we therefore obtain a global sequestration estimate by forestation in semi-arid areas, by extrapolating to 20% of the global semi-arid area, where the total area comprises ~18% of the global land surface (~27 million km²). The 20% estimate takes into account that forests should be planted in regions of minimum albedo effect and sufficient water supply. Based on the above considerations, we extrapolate to 3.0 petagram CO2 (3.0 billion metric tons) per year organic carbon sequestration for 20% forestation of the global semi-arid area.

4. THE SEQUESTRATION OF INORGANIC CARBON BENEATH FORESTED SEMI-ARID LANDS
4.1 CHEMICAL AND ISOTOPIC REACTIONS AND WATER FLOW RATE RELATED TO SOIL INORGANIC CARBON (SIC) SEQUESTRATION

Inorganic carbon, in the form of allogenic (transported) and pedogenic (produced in situ in the soil) carbonates are both found in the soils in semi-arid soils under semi-arid forests. The allogenic calcite can be derived from erosion of local limestone or fine calcite particles that have been transported great distances by the wind (Ganor et al. 2009). Their origin was generally old marine carbonates. They do not represent modern sequestration of atmospheric carbon dioxide. Only the pedogenic carbonate comprises a carbon sink. Carbon isotope ratios ($^{13}$C/$^{12}$C and $^{14}$C/$^{12}$C) were measured as a function of depth in the liquid and solid phases of soil profiles in the USZ, and then presented in standard $\delta^{13}$C and $\Delta^{14}$C notation (Carmi et al. 2015). The $\delta^{13}$C (%) for example is the relative deviation of the $C^{13}/C^{12}$ ratio of the liquid or solid soil sample compared to that of a standard material.

The old residual limestones were marine in origin, and have a characteristic marine signature of $\delta^{13}$C = ~ 0‰. The $\delta^{13}$C of the bicarbonate, originating from isotopic depleted root-exhaled CO$_2$ ($\delta^{13}$C = ~26‰, C3 plants) is slowly enriched by exchange (continuous dissolution and precipitation) with the relict marine carbonate to approximately half this value in the USZ (Clark and Fritz 1997). Radiocarbon is a unique tracer for labeling atmospheric derived sources of carbon gas, liquid and solid phase carbon within the USZ. The host sediment initially contains no 14C. This carbon isotope is produced in the upper atmosphere. Relict or allogenic calcite found within the soil profile is limestone of marine origin. Besides its $\delta^{13}$C, it is readily distinguished from pedogenic carbonate soil calcite in that it contains no radiocarbon ($\Delta^{14}$C = -1000, zero 14C). By tracking carbon isotopes ($^{13}$C, $\delta^{13}$C, $\Delta^{14}$C) as a function of depth in the liquid and solid phases of soil profiles in the USZ, it has been demonstrated that the source of the precipitated calcite was originally CO$_2$ respired from tree roots, and coming from bacterial decomposition of organic matter (Carmi et al. 2019). A tree’s roots exhale CO$_2$ into the soil after some of the tree’s glucose (produced by photosynthesis) has been oxidized to supply energy for the tree’s cellular processes.

The CO$_2$ in the soil gas of the USZ can attain partial pressures many times above the ambient atmospheric CO$_2$ partial pressure. This facilitates the reaction:

$$CO_2(gas) + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^-$$  \hspace{1cm} (3)

in which soil CO$_2$ combines with soil moisture to form a carbonic acid solution, which rapidly dissociates to $H^+$ and bicarbonate (HCO$_3^-$). When increasing dissolved inorganic carbon (DIC) concentration (due in part to evaporation) leads to saturation, and then exceeds the solubility of calcite, the DIC (mainly bicarbonate) and the soluble bivalent cations (mainly Ca$^{2+}$) combine to form pedogenic calcite within the USZ:

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 \downarrow + CO_2 \uparrow + H_2O$$  \hspace{1cm} (4)

Rate limiting factors for these reactions include the abundance of Ca$^{2+}$ (or Mg$^{2+}$), and the partial pressure of CO$_2$. Early studies of soil gas CO$_2$ within the USZ had concluded that most CO$_2$ respiration was confined to a depth of 1 to 2 meters (Bacon and Keller 1998). In addition, it had been assumed that there is a rapid release of tree root exhaled CO$_2$ back into the atmosphere from the soil (Raich and Potter 1995). Both of these assertions may not apply to semi-arid zones. In search of water, semi-arid trees can have roots that descend several times the depth of those of temperate regions. For example, Bacon and Keller (1998), studying CO$_2$ in the USZ of a semi-arid region, noted that the CO$_2$ gas concentration increased down to the water table (at a depth of 7.5 meters). This was attributed to root respiration combined with bacterial action on organic matter. Thus, while a fraction of the gas may be released to the atmosphere, its slow rate of diffusion enables the gas to reach an equilibrium between leaving the USZ and remaining there at high soil-gas CO$_2$ partial pressures. The gas that is
retained has been derived from the atmosphere. As long as the gas stays within the USZ, it is effectively sequestered. However, the mass of the gas participating in this sequestration is not yet well determined.

The very increased depth of the root systems (Canadell et al. 1996) in drylands can further enhance CO₂ sequestration through CO₂-rich recharge (Wen et al. 2021); considering increased weathering, often aided by symbiotic Mycorrhiza fungi (Bonneville et al. 2011). The chemical weathering of rocks converts soil-gas CO₂ into dissolved inorganic carbon (DIC), which then can descend into the water table or precipitate in the USZ.

Considering Eq. 4, it had been previously accepted (Monger et al. 2015) that if the calcium ions were not derived from silicates (see Eq. 5 below), no atmospheric CO₂ would be sequestered. This follows since for every mole of calcite formed, one mole of CO₂ would be returned to the atmosphere. However, while Eq. 4 suggests such a conclusion, it does not describe the actual situation in the soil column. In Israeli soils, there are exogenous sources of bivalent cations, particularly Ca²⁺, that include calcium ions desorbed from the exchange sites on clays imported by air-borne dusts (Singer 2007); as well as calcium brought in by rain or sea spray, depending on the distance from the coast. Moreover, the Eq. 4 reaction occurs within the USZ soil column, which is generally thick in semi-arid regions. Only the topmost part of the USZ is in direct contact with the atmosphere. Gas from this location most likely diffuses out of the soil. However, CO₂ released lower in the soil column more likely enters and mixes with the relatively high partial pressure CO₂ in the USZ. The high pressure facilitates its reaction with soil moisture and the formation of bicarbonate, which then combines with calcium or magnesium ions (Carmi et al. 2019). Where rainfall is plentiful, this precipitate dissolves. In semi-arid regions, where rainfall is sparse, precipitated calcite can remain stable for millennia (Cerling 1984).

We quantify the annual sequestration rate by analyzing the soil core samples, to determine the decreased concentration (due to calcite precipitation) versus depth (time) of bicarbonates in the liquid phase of the USZ. We find thereby that bicarbonates, originating from root exhalation, are isotopically depleted and are incorporated within the USZ as the calcite precipitates. The techniques developed and used for sampling the soil moisture and the inorganic carbon via isotopic measurements are presented in Carmi et al. (2007, 2009). The depth profiles were converted to time profiles, using the 11 cm/year infiltration rate. Using data from the mid-core depth (2.2 meters) as representative, the calcite deposition rate into the sediment was found to be 22 mg CO₂ from the atmosphere per year per liter of sediment (Carmi et al. 2019).

For future inorganic sequestration measurements at other forests, such isotope data is desirable, but may not be necessary. It may be sufficient to determine the decrease of DIC concentration down the profile (due to calcite precipitation) versus depth (time) of bicarbonates in the liquid phase of the USZ.

4.2 THE CO₂ GAS PHASE IN SEQUESTRATION WITHIN THE USZ

Although desert areas have been rather neglected in global carbon budgeting, Ma et al. (2014) note that these regions have strong downward CO₂ fluxes. The increased depth of the root systems in drylands (Canadell et al. 1996) further enhances CO₂ sequestration by increasing CO₂ recharge (Wen et al. 2021). This in turn increases weathering. The chemical weathering of rocks converts soil CO₂ into dissolved inorganic carbon (DIC, mainly bicarbonate 2HCO₃⁻) which can then descend into the water table or precipitate in the USZ. Consider the weathering of silicate rocks, using the calcium form of plagioclase (anorthite) as a representative example, via the reaction:
\[
Ca_2Al_2Si_2O_8 + 2CO_2 + 3H_2O \rightarrow Ca^{+2} + Al_2Si_2O_5(OH)_4 + 2HCO_3^{-} \tag{5}
\]

All of the HCO_3^- formed and released to solution comes from atmospheric CO_2. Likewise, for carbonate rock, the enhanced weathering through enriched CO_2 in the recharge facilitates the transformation of atmospherically derived CO_2 into DIC, by dissolution of limestone:

\[
CaCO_3 + CO_2 + H_2O \rightarrow Ca^{+2} + 2HCO_3^{-} \tag{6}
\]

In both cases, contemporary and past weathering of rocks have converted atmospheric CO_2 into DIC. This DIC can now be stored for long periods in the aquifer. Note that the rainfall recharge theoretically should be mildly acidic (Eq. 3), having a pH of 5.7 (at 25 °C). However, in the Levant, windblown dust is ubiquitous. The dust in the clouds contains plentiful fine carbon minerals (Ganor et al. 2009). Within the cloud, the acidity is neutralized by interaction with the carbonate minerals (Eq.6) (Loye-Pilot et al. 1986). Thus, when the very dilute recharge water falls upon the ground, it is not aggressive. It only becomes so after it enters the soil zone, and is influenced by CO_2 soil gas. Thus, the recharge water dissolves atmospheric derived CO_2 from the soil, and then incorporates it as DIC. Some added quantity of CO_2 from the dissolution of the relict carbonate is also incorporated as DIC (mainly bicarbonate), either from the dust or by erosion of local limestones. This second addition does not originate from modern atmospheric CO_2. Together, these two components descend towards the water table. In Israel, the ground water so charged contains roughly 270 mg/L of HCO_3^-; or more than 0.25 g per liter of aquifer water. All of this is collected as the rainwater infiltrates through the USZ, although only a fraction is formed from atmospheric CO_2. The percentages of these two DIC components can be calculated by measuring the $\delta^{13}C$ of the aquifer’s bicarbonate DIC, as discussed above. A significant amount of atmospherically derived CO_2 can be thereby determined to have been incorporated and sequestered into the ground water. This DIC is now be stored for long periods in the aquifer. Once within the aquifer, the water chemistry is generally stable. Consequently, aquifer water under semi-arid forests may also be considered a vast sink of atmospheric CO_2. Li et al. (2015) indeed did report that water beneath deserts has been an unrecognized sink for stored carbon, principally as the bicarbonate anion component of DIC. Unfortunately, the chronologic controls are weak, so that the age of these aquifer waters and their flow rates is generally poorly constrained. Thus, we cannot reliably estimate the annual rate of this bicarbonate injection into the aquifers, and therefore the rate of such past sequestration of inorganic carbon. An estimate though of the modern total global flux of atmospheric derived CO_2 into groundwater as DIC has been calculated as ~0.2 Pg C per year (Kessler and Harvey 2001).

5. EXTRAPOLATING THE YATIR USZ RATE OF SOLID INORGANIC CARBON SEQUESTRATION TO GLOBAL SEMI-ARID REGIONS

Forestation related calcite precipitation data in the USZ of other semi-arid regions are not yet available. Many geographical areas may have appreciably thicker USZ soil profiles than does Yatir. To estimate global sequestration in the semi-arid USZ, in the absence of more data, only a “gedanken” estimate is possible. We assume that the topsoil composition and calcite precipitation rate at Yatir is representative of the global semi-arid area (~27 million km², corresponding to 2.7 billion ha), ~18 % of the global surface area (Lal 2004) following forestation. The calculations given here are only very rough estimates, based on the 22 mg yr⁻¹ L⁻¹ rate of calcite precipitation in the USZ at Yatir.

We assume a 6-meter global average depth of root respiration in the USZ of semi-arid regions. This takes into account that plant roots extend downwards to much greater depths in semi-arid compared to temperate zones (Canadell et al. 1996). The estimated global soil volume is then

\[6*27*10^{12} \; m^3 = 1.62*10^{17} \; liter.\]

Assuming that 22 mg CO_2 per year per liter characterizes the global inorganic sequestration rate gives an estimated global sequestration rate of

\[0.2*1.62*10^{17}*22*10^{-3} = \]

\[3.58*10^{15} \; kg \; CO_2 \; per \; year.\]

\[3.58*10^{15} \; kg \; CO_2 \; per \; year = 3.58*10^{15} \; Pg \; CO_2 \; per \; year.\]
7.12*10^{14} \text{ gram per year or } -0.8 \text{ Pg}, corresponding to \sim 0.8 \text{ billion metric tons of inorganic CO}_2 \text{ per year, for } 20\% \text{ of the global semi-arid regions. The } 20\% \text{ choice again reflects our conservative estimate, as reliable data are not available that quantitatively evaluates the potential for economically self-sustaining forestation over the world's semi-arid zone. It could be greater than the } 20\% \text{ value considered here. Significantly, the precipitated calcite does not dissolve in low rainfall semi-arid regions. Converting to grams per square meter gives 132 \text{ gram inorganic CO}_2 \text{ per square meter per year } (7.12*10^{15}/5.4*10^{15}). \text{ This value is roughly } 25\% \text{ of the value of } 550 \text{ grams organic CO}_2 \text{ (150 grams organic C) per square meter per year determined by Qubaja et al. (2020B) at Yatir.}

Additional data are needed in Israel and elsewhere to determine more representative global organic and inorganic carbon sequestration rates. As discussed above, for example, the infiltration rates for inorganic sequestration can be higher at different semi-arid regions, which would in turn affect the derived sequestration rates. However, our rough estimate here already suggests a significant potential to sequester inorganic carbon.

6. EXTRAPOLATING THE YATIR ORGANIC PLUS INORGANIC CARBON SEQUESTRATION RATE TO GLOBAL SEMI-ARID REGIONS

The global semi-arid forestation sequestration annual rates of organic and inorganic of CO\textsubscript{2} have been estimated above as 3.0 billion tons and 0.8 billion tons respectively. The total organic plus inorganic sequestration rate of \sim 4 billion tons CO\textsubscript{2} per year then represents roughly 20\% of the present annual increase of 20 billion tons of CO\textsubscript{2} to the present global atmospheric CO\textsubscript{2} reservoir of \sim 3200 billion tons. The uncertainty in this 4 Pg per year value is high, since data are not available to determine how representative Yatir is of the global semi-arid area; and because global data on the albedo effect as well as the vegetation carrying capacity are not available. Notwithstanding, this 4 Pg per year estimate already demonstrates the global potential for the reduction of atmospheric CO\textsubscript{2} and its long term sequestration in semi-arid regions by the relatively simple and inexpensive expedient of forestation. It also is implicit that there is a need for further measurements. More significantly, however, there is already a clear justification for implementing a global land management policy of widespread tree planting in semi-arid regions. More explicitly, the sequestration of atmospheric CO\textsubscript{2} via global semi-arid forests may represent a sustainable and economic method to help suppress the rate by which CO\textsubscript{2} is increasing in the atmosphere.

7. TREE PLANTING TECHNOLOGIES

Which tree species should be planted for global forestation? One should encourage biodiversity while avoiding monocultures. It is important to achieve rapid sequestration. Bamboo for example grows very fast (Aseri et al. 2012; Osei et al. 2019). This can be replaced over time by other types of trees which thrive in semi-arid regions, including the Moringa tree (Little 2016), which is as well a hardy food source. Another example is the jojoba plant that provides commercial natural oils for pharmaceuticals and cosmetics. These potential commercial exemplars may also perform both above and below ground carbon sequestration. It is important to develop a long-term tree planting strategy that optimizes total sequestration and commercialization, to offset the costs of planting and maintaining a forest. Ideally, the trees should be native to the area, which would maximize their chances for survival. The trees chosen should be able to effectively reproduce and repopulate over time. It would also be beneficial to stack various ecosystem services into one reforestation project; like carbon sequestration, biodiversity, soil stabilization, water retention.

In Israel, KKL-JNF (2022) is responsible for forestation. Traditional planting methods are used. Tourists and the public are invited to participate. In Africa, Betterglobe AS (Betterglobe 2022)
and Better Globe Forestry Ltd (BGF 2022) aim to plant and care for billions of trees in semi-arid areas, also using traditional planting methods.

Reboot Reforestation (Morris 2022; Seedball 2022) employs innovative drone and seedball technology that utilizes heavy lift drones to deliver seedballs to unforested areas for forestation purposes. Though this technology was successful in wetter climates, it remains to be tested in arid zones (Morris 2022). Alternatively, Landlife (Lovenstein 2022) uses a patented product that enables trees to grow in dry and degraded land. Its Cocoon™ planting technology offers a low-cost and scalable way to provide water and shelter to planted trees for the first year of a seedling’s life. They claim 75-95 % high survival rates in semi-arid areas (Carabassa et al. 2022). During two years of tests, it was demonstrated that the Cocoon effectively increased seedling survival, especially under dry growing conditions (low rainfall, soils with low water holding capacity). The Cocoon also allowed for higher growth of a variety of species (olive trees, holm oaks, and Aleppo pines) (Lovenstein 2022).

8. CARBON CREDITS

Planting new forests and maintaining existing forests are important in order to offset widespread, worldwide deforestation, as has been taking place in the Amazon rain forests. It is also needed to offset widespread, high levels of forest die-off by forest fires, as has been occurring more frequently worldwide due to drought and rising temperatures. Carbon credits may become valuable and play a supportive forestation role if ever the world’s governments enact supporting legislation. They would be valuable for forests established in the future, but not necessarily for existing forests like Yatir. The reason is that the carbon credit markets so far have a rule of thumb that only entities who make a positive change to their land management approach are eligible for credits. Yatir may possibly be eligible, as this forest has been continuously changing, converting from a single-species, even-aged forest stand into a mixed-aged stand. In addition, Yatir and other existing forests would demonstrate a very positive change to their land management approach if and when they start using our estimation and/or measurement methods to evaluate sequestration rates. However, such changes may still not satisfy the carbon credit markets. One should try to persuade the carbon markets to soften their rule of thumb, since maintaining existing forests (such as the disappearing Amazon Rainforest) is critically important.

9. IMPLICATIONS REGARDING ORGANIC PLUS INORGANIC CARBON SEQUESTRATION

To date, the semi-arid regions are generally 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. The sequestration described here is restricted to semi-arid regions. Far from being a drawback, this gives added economic potential to these marginal regions. Advantages are providing forestry employment by replacing marginal agriculture or herding, providing long-term underground storage of carbon, and harvesting the above ground biomass (organic carbon) for commercial products such as lumber or charcoal. Semi-arid forestation (afforestation and reforestation) can achieve carbon sequestration at lower cost than required for major engineering endeavors for fulfilling climate goals.

A global land management policy suggests itself, one of widespread tree planting in semi-arid regions. Significantly, the proposed forestation efforts would not come at the expense of cropland and food budget, as would be the case in more temperate regions. Such global forestation would promote organic plus inorganic carbon sequestration. Almost paradoxically, many areas around the world that today are rainfall deficient often contain important groundwater reserves that can be employed for
forestation projects (e.g., Herczeg et al. 1991; Kronfeld et al. 1993; Nativ and Smith 1985; Pavelic et al. 2012; Verhagen et al. 1991). These aquifers can be found under drylands in all of the inhabited continents. They range in size from relatively small sources, exploited on a local level, such as those underlying West Texas (e.g., Trinity or Hosston aquifers) (Verhagen et al. 1991), or the Djeffara in southeastern Tunisia (Trabelsi et al. 2012), to huge aquifers such as Ogallala, or the Milk aquifer that underlies large sections of central and north-western North America, the Great Artesian Aquifer of Australia, and the Nubian Sandstone aquifer that underlies North Africa. These reserves are not related to the present rainfall regime and can be considered as “fossil” waters, replenished during past pluvial periods (Verhagen et al. 1991). In most cases, the bicarbonate anion is the dominant anion in these fresh water reserves. A conservative 0.25 gram of bicarbonate can be found in each liter of most of these aquifers. Thus, a very large quantity of atmospherically originating CO\(_2\) has been stored in these aquifers in the past. Since the infiltration rate is not known, the carbon sequestration rate is also not known. The amounts are nonetheless appreciable.

10. CONCLUSIONS

Forestation in semi-arid regions would convert atmospheric carbon to organic biomass, and would also provide long-term sequestration as insoluble pedogenic inorganic carbonate within the USZ. The global sequestration rates presented here are only rough estimates, based on the single measured value at Yatir of 22 mg per liter per year rate of precipitation of inorganic carbonate, and 550 grams organic CO\(_2\) per square meter per year. These values have been extrapolated to what we considered to be a very conservative estimate of 20% of the global semiarid area that could potentially be afforested at reasonable cost. Many factors may affect our estimate, such as soil thickness, soil structure, rate of water descent, soil pH and Alkalinity, temperature, soil calcium composition, water chemistry, type of trees, etc. Therefore, the global sequestration rate presented here is only a first tentative estimate. Additional measurements are needed to bolster the database, and thus refine the estimates of the potential amounts of CO\(_2\) that can be sequestered in semi-arid regions worldwide. Nevertheless, the estimated total carbon sequestration rate suggests a significant potential to achieve long-term carbon sequestration. Tentatively, sequestration of atmospheric CO\(_2\) as inorganic and organic carbon in semi-arid forests represents a sustainable and economic method to help suppress the rate by which CO\(_2\) is increasing in the atmosphere.

Moreover, the planting of trees will also have positive climate cooling effects, prevent encroaching desertification, supply needed oxygen to the world, contribute to increased precipitation, improve soil structure and quality and soil stability, reduce erosion and runoff, reduce soil biogenic nitric oxide emissions, reduce air particulate pollution in nearby urban environments, and provide wild life habitat and recreational facilities.
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