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Abstract

Drylands forestation offers the potential for significant long-term sequestration of atmospheric CO_2. Here we consider sequestration of both organic and inorganic carbon by a planted semi-arid forest, based on carbon that originates from atmospheric CO_2. Measurements at Israel's Yatir forest give a sequestration rate of ~550 g CO_2 m^{-2} yr^{-1} as organic carbon in the trees' biomass. In addition, ~216 g CO_2 m^{-2} yr^{-1} precipitates as calcite ($CaCO_3$) in the soil due to a combination of microbial activity on organic soil carbon, and the formation of soil carbonic acid (H_2CO_3) that arises from the reaction of soil water with CO_2 exhaled from tree roots. Significantly, low rainfall in drylands precludes dissolving precipitated calcite. Published estimates restrict the potential drylands surface available for sustainable forestation to ~4.5 million km^2, only ~10% of the global drylands. The dominant limitation is the apparent lack of water. However, immediately under many drylands, there are paleowaters (fossil water) that had recharged underlying aquifers during prior wetter climatic regimes. Conservatively, including fossil water, at least ~9.0 million km^2 is available for afforestation. Such an area may yield a potential total annual sequestration rate of ~7.0 Gt CO_2 yr^{-1}, divided between 5.0 Gt CO_2 yr^{-1} (organic) and 2.0 Gt CO_2 yr^{-1} (inorganic). This represents a respectable ~35% of the annual rate of atmospheric CO_2 increase. However, considering the reduction in land surface albedo (reflectivity), the effective cooling would be ~5.0 Gt CO_2 yr^{-1}. Drylands reforestation would provide additional area for sequestration. Overall, our estimate demonstrates the efficacy of implementing a global land management policy of widespread afforestation and reforestation in drylands regions.

Keywords: carbon sequestration; drylands forests; climate change; fossil water

1. Introduction

The twin ecological problems of increasing global warming and ocean acidification are inextricably intertwined with increasing levels of atmospheric carbon dioxide. CO_2 is currently being emitted globally at roughly 40 billion tons per year (40 Gt CO_2 yr^{-1}). About 50% of these emissions accumulate in the atmosphere, 30% in the ocean, and 20% on land [1,2]. Since the Industrial Revolution, the CO_2 concentration in the atmosphere has risen from ~280 ppmv to ~427 ppmv at present [3]. The global atmospheric CO_2 reservoir of ~3200 billion tons is presently increasing annually by ~20 billion tons. This increase is occurring mainly through the burning of fossil fuels, forest fires and deforestation. The released CO_2 is a potential cause of both increased global warming and ocean acidification [4]. Indeed, the global Conference of the Parties climate pacts call for the world's nations to significantly reduce CO_2 emissions, to prevent (by 2030) global warming from rising more than 1.5 ℃ above pre-industrial levels. Slowing the rise in global temperatures also requires simultaneously proactively reducing atmospheric CO_2 concentrations. Relatedly, very

expensive, large climate engineering projects have been proposed by CO_2 removal (CDR) and solar radiation management (SRM) [5].

To date, CO_2 greenhouse gas and its potential for global warming get most of the media attention. However, the problem of increasing ocean acidity has a direct bearing on oceanic health and the global food supply. The pH of the ocean has been decreasing since the pre-industrial period due to increasing levels of atmospheric CO_2 [4]. The ocean has so far served as a sink for roughly 30% of CO_2 released to the atmosphere. CO_2 when combined with H_2O forms H_2CO_3, carbonic acid. The increasing oceanic carbonic acid concentration has led to increased ocean acidity. This in turn inhibits the ability of the oceans to absorb more atmospheric CO_2. The pH of ocean water is presently 8.1 [2], which represents a 30% increase in acidity since the pre-industrial era. This increase correlates with anthropogenic releases of CO_2 [6]. The increased acidity puts stress on planktonic organisms that build their shells from $CaCO_3$ (calcium carbonate or calcite), as well as on other marine life forms [2]. Solving this problem requires reducing the atmospheric CO_2 concentration in contact with the ocean surface. Thus, the solution to both ecological problems involves the removal of atmospheric CO_2, coupled with its long-term storage. Such a solution may be found within the carbon cycle, whereby soils and trees abstract atmospheric CO_2 and store large stocks of global carbon. Simply, trees take in CO_2 through the process of photosynthesis, which converts the carbon to organic carbon which makes up almost half of a tree's mass. Organic matter is transferred to the soil by tree litter, and decomposition of fallen trees, aided by microbial action to form soil organic matter (SOC). Atmospherically derived CO_2 can also be removed by forests transforming this gas into inorganic carbon, either as soil inorganic carbon (SIC) or as dissolved inorganic carbon (DIC). We elaborate on the processes below. Forestation is a simpler and less expensive method for removing atmospheric carbon than massive and expensive high tech engineering projects. But where should this needed large-scale planting be carried out? Forestation efforts can successfully be carried out in temperate zones. However, this is where the most productive agriculture is carried out. Refs. [7] and [8] pointed out that attaining mandated climate goals via temperate zone forestation would overtly reduce arable lands available for food production. Moreover, large amounts of fertilizer would be required, whose runoff could degrade water supplies. Thus, such a program in temperate zones may come at an egregious cost.

Drylands may be more suitable than temperate lands for afforestation efforts to remove atmospheric CO_2 by organic and by inorganic carbon sequestration. Drylands make up over 40% of the world's surface [9], covering almost 45 million km^2. This includes semi-arid, arid and hyper-arid regions [10]. Ref. [11] include the sub-humid (600-1200 mm) annual precipitation zone [10]. This latter region can store organic carbon, but may be less efficient for sequestrating inorganic carbon. The reason is that precipitated calcite is less stable under wetter conditions compared to the semi-arid (<600 mm precipitation) zone [10], where the calcite is stable. The semi-arid and desert regions are generally less populated and provide low agricultural and economic value. They would be prime regions for forestation were it not that the climate is hot and harsh, and that sufficient water appears to be lacking. Thus, most of these regions have not been previously considered for forestation [12,13]. For example, the latter reference assumed that only 10% of the drylands area could sustain forests.

Moreover, in climate mitigation modeling, there is a playoff between two first-order climate-influencing factors: the reflectivity of the land and the amount of CO_2 in the atmosphere. The higher the reflectivity (albedo), the less is the heating due to the incoming solar radiation. The arid lands are regions of high albedo. By planting trees, the albedo decreases as dark vegetation replaces reflective landscapes. The shift in reflectively results in greater radiative heating which may override the cooling effect of atmospheric CO_2 reduction; despite higher evapotranspiration, or increased cloud cover [14].

Thermal emission in the infrared wavelength range from the Earth back to space is crucial for the Earth's energy balance and resultant equilibrium average temperature. CO_2 in the atmosphere efficiently intercepts and captures some of this infrared energy, and then re-emits part of that energy back to the Earth. Thereby, extra heat is trapped on the Earth, which increases the Earth's equilibrium temperature. This is popularly known as the greenhouse effect. That is, CO_2 greenhouse gas contributes to warming as its concentration rises; alternatively, a decline in its levels would lead to a cooling effect.

Based on the Yatir Forest studies, Ref. [12] assumes a 1.5 billion tons per year organic carbon sequestration in the forestable 4.5 million km^2 of drylands. In this reference, and more recently [15], they estimated a negative albedo effect equivalent to ≈ 1.0 billion tons CO_2 per year in this same area. Thus, they estimated a net effective sequestration of only 0.5 billion tons CO_2 per year. Their albedo effect reduction is close to that estimated by [16] who studied forest albedo across the whole USA. On average, they found that albedo offsets almost 50% of the cooling benefit attributable to organic carbon sequestration by a forest. Considering the estimate of only 0.5 billion tons CO_2 per year, Ref. [15] concludes that global drylands forestation would yield only minimal positive cooling benefits. The reduced albedo negated optimism that had been expressed for global cooling through forestation [17], particularly in drylands [18,19].

The above studies were restricted solely to the effects of forestation on organic carbon sequestration. We reevaluate the potential for global cooling by atmospheric CO_2 removal by organic and inorganic processes, while also considering the effects associated with the related albedo reduction. We take into account measurements of both organic and inorganic carbon sequestration in the same Yatir semi-arid forest. We conclude that drylands regions are important for future afforestation efforts. The harshest of these drylands may still support forests, whenever there are plentiful underlying fossil groundwaters.

We start with a preview of our own estimate of global drylands carbon sequestration. We begin with the Ref. [12] estimate that 4.5 million km^2 of semi-arid and dry sub-humid drylands are potentially forestable. We estimate global organic carbon sequestration rates in this area to be ~2.5 billion tons CO_2 yr^{-1}. This is higher than the Ref. [12] estimated value of ~1.5 billion tons CO_2 yr^{-1}. Ref. [20] measured an organic sequestration rate in Yatir forest of 150 grams of carbon per m^2 per year, which equates to 550 grams of CO_2 per m^2 annually. This translates to 2.5 billion tons of organic CO_2 per year over an area of 4.5 million km^2. We then add an estimated 1.0 billion tons of inorganic CO_2 per year (described in Sections 4 and 6) to get 3.5 billion tons CO_2 sequestered per year. Taking into account the presence of fossil water (described in Section 7), we double the potential usable area to 9.0 million km^2. This area could then sequester approximately 7.0 billion tons of CO_2 per year. However, considering the anticipated reduction by the albedo effect [12], the estimated global cooling effect would effectively equate to only 5.0 billion tons of CO_2 sequestered annually. This value corresponds to a 25% of the annual increase of 20 billion tons of CO_2 presently accumulating in the global atmosphere; a significant 10 times larger than the 0.5 Gt CO_2 yr^{-1} effective value estimated by [12].

We note that removing 7.0 Gt CO_2 from the atmosphere would disturb the equilibrium between atmosphere, soil and oceans; approximately 50% of CO_2 emitted to the atmosphere presently accumulates in the atmosphere, 30% in the ocean, and 20% on land [2]. Equilibrium would be restored over time by the soils and oceans emitting CO_2 to the atmosphere; such that the resultant effective CO_2 reductions per year would be ~3.5 Gt, ~2.0 Gt, and ~1.5 Gt for the atmosphere, oceans and soil, respectively. Considering this expected equilibration, a very important additional benefit of forest carbon sequestration would be a reduction in ocean acidity.

2. Yatir Forest Study Area and Methods of Study

Israel's planted Yatir forest is a 28 km^2 Aleppo pine forest growing at the semi-arid timberline with no irrigation or fertilization [21]. Jewish National Fund (Keren Kayemeth LeIsrael) foresters have planted ~4 million trees at Yatir since 1964. This site (GPS: 31°20′ N, 35°03′ E) is situated above the carbonate Mountain Aquifer at an elevation of ~650 m above sea level, at the edge of Israel's Negev desert. It is the largest forest in Israel [21].

The mean annual precipitation is ~285 mm, falling solely during the winter rainy season as high intensity rain events, while the remainder of the year is hot and dry. The mean annual potential evaporation and precipitation are 1,600 mm and 285 mm, respectively. The runoff is negligible. The groundwater table is located at greater than 300 m depth [22,23]. Conditions are at the drier and hotter limit (Aridity Index AI = 0.18) compared to the world's semi-arid (AI = 0.2-0.5) region [10]. The rate of rainwater infiltration at Yatir was measured as ~11 ± 2.2 cm yr^{-1} using Tritium in water as a

tracer [24]. Water including T_2O is extracted from soil water samples of a sediment profile as a function of depth [25]. Despite the present low precipitation, the Yatir forest is productive and stores organic carbon relatively effectively without irrigation or fertilization [26].

3. Organic Sequestration

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 stoma combines with H_2O to produce organic carbon, glucose ($C_6H_{12}O_6$), as well as O_2 oxygen as a byproduct. This process can be represented by the following equation:

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2 \tag{1}$$

Trees utilize this glucose to form biomass, such as wood. The reverse reaction, either by direct oxidation or involving catabolic reactions, releases the stored carbon either directly to the atmosphere or into the soil profile by root exhalation:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \tag{2}$$
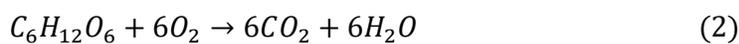
The organic carbon residence time for this sequestration (Eq. 1) is at least 150 years, considering the typical 100-150 year life span of Aleppo pines and their long decomposition time after falling. Thus, extensive afforestation has been proposed as being effective in sequestering atmospheric CO_2, both as Aboveground Biomass Carbon (ABC), as well as in the roots [27–30]. The carbon is in the form of wood above ground (trunk, branches, bark) and below ground (roots), leaf litter, and tree products (nuts, acorns, fruit). Approximately 50% of a tree's biomass is composed of carbon.

Israel's Yatir Forest was found to have an organic carbon sequestration rate of 150 grams per square meter per year, corresponding to 550 g organic CO_2 m^{-2} yr^{-1}. This corresponding to 2.5 billion tons CO_2 per year in 4.5 million km^2, higher than the previously estimated value of 1.5 billion tons (organic) CO_2 yr^{-1} for this area [12]. The value 550 g organic CO_2 m^{-2} yr^{-1} was obtained using the data of a 15 year long monitoring program that combined eddy covariance (EC) flux measurements as well as carbon and nitrogen stock counting inventories. The EC method is a key atmospheric measurement technique employed to determine net vertical forest-atmosphere exchange fluxes of CO_2, water vapor, heat, etc. Uncertainties (~20%) were assessed by comparing stock-based and flux-based approaches [20]. Ecosystem-scale accounts of carbon stocks (CS) were estimated in permanent study plots involving tree size parameters and soil organic carbon (SOC) and then converted to CS with allometric equations and soil sample analyses [31,32]. The dependent variable in these equations was biomass, and the main independent variables were tree diameter at breast height (DBH) and tree height. This stock-based approach is generally performed on a few small plots that need to be scaled up. The original forest inventory assessment was performed in 2001 [33] and was repeated 15 years later [20] on the same five 30 × 30 m^2 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 represents the average increase in carbon in soil and tree CS over the observation period. We assume in the discussion that the carbon sequestration rates at Yatir forest are representative of global drylands.

4. Inorganic Sequestration

The Yatir forest's inorganic carbon sequestration data includes gas and soil samples; from which the gas composition, mineralogy, soil moisture and other parameters were determined [34]. The samples were collected in depth profiles extending from the surface to a maximal depth of ~4.5 m. It has been estimated that on a global scale, 2.3 trillion tons of carbon in the form of SIC resides in the upper 2 meters of soil profiles [35]. Despite the significant quantity of stored carbon, its precise value remains difficult to assess

for carbon mitigation purposes, because both allogenic (transported residual carbonates) and pedogenic (recently formed *in situ* in the soil) carbonates are present in dryland forests. The allogenic calcite origin is generally remnants of old marine carbonates. They do not represent modern sequestration of atmospheric CO_2. Only the pedogenic carbonate comprises an active carbon sink.

In the present study, carbon isotope ratios (C^{13}/C^{12} and C^{14}/C^{12}) were measured as a function of depth in the liquid and solid phases of soil profiles in the unsaturated zone (USZ), and then presented in standard $\delta^{13}C$ and $\Delta^{14}C$ notation [24]. The old residual limestones have a characteristic marine signature of $\delta^{13}C$ = ~0 ‰. The $\delta^{13}C$ of the bicarbonate (HCO_3^-), originating from isotopic depleted root-exhaled CO_2 ($\delta^{13}C$ ~ −26 ‰, C3 plants), is slowly enriched as a function of depth by exchange with the relict marine carbonate to approximately half this value in the USZ [36]. Radiocarbon is a unique tracer for labeling atmospheric derived sources of carbon gas, liquid and solid carbon phase within the USZ. The host sediment initially contains no ^{14}C. This radioactive carbon isotope is produced in the upper atmosphere. Allogenic calcite, besides its $\delta^{13}C$ signature, is readily distinguished from pedogenic carbonate soil calcite in that it contains no radiocarbon ($\Delta^{14}C$ = −1000, zero percent modern carbon). By tracking carbon isotopes (^{12}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 was demonstrated that the source of a significant portion of the precipitated calcite was originally CO_2 respired from tree roots [37]. 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 [36]. This facilitates the reaction:

$$CO_2 \ (gas) + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^- \qquad (3)$$
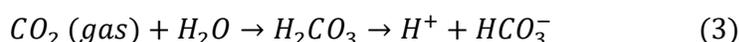
in which soil CO_2 combines with soil moisture to form a carbonic acid solution, which rapidly dissociates to H^+ and bicarbonate (HCO_3^-). An increasing dissolved inorganic carbon (DIC) concentration (due in part to evaporation) leads to saturation, subsequently exceeding the solubility of calcite. The DIC (mainly bicarbonate) and the soluble bivalent cations (mainly Ca^{2+}) then combine to form pedogenic calcite within the USZ:

$$Ca^{+2} + 2HCO_3^- \rightarrow CaCO_3 \downarrow + CO_2 \uparrow + H_2O \qquad (4)$$
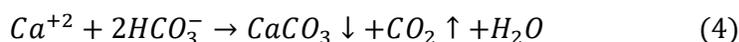
Rate limiting factors for these reactions include the abundance of Ca^{2+} (or Mg^{2+}), and the partial pressure of CO_2. Considering Eq. 4, it had been previously accepted [38] that if the calcium ions were not derived from silicates (see Eq. 5 below), no atmospheric CO_2 would be sequestered. This would follow if for every mole of calcite formed, one mole of CO_2 is returned to the atmosphere. While Eq. 4 would suggest such a conclusion, it does not describe the actual situation in the soil column. In Israeli soils, as in soil of many regions, there are exogenous sources of bivalent cations, particularly Ca^{2+}, that include calcium ions desorbed from the exchange sites on clays imported by air-borne dusts [39]. In addition, calcium can be brought in by rain or sea spray; and its concentration in the soil would depend on the distance from the coast [40]. Moreover, the Eq. 4 reaction takes place 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 does diffuse out of the soil. However, CO_2 released lower in the soil column is more likely to enter and mix with the relatively high partial pressure CO_2 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 [37]. Where rainfall is plentiful, this precipitate dissolves. In drylands regions, where rainfall is sparse, precipitated calcite can remain stable for millennia [41].

The techniques developed and used for sampling the soil moisture and the inorganic carbon via isotopic measurements are presented in [42]. The depth profiles were converted to time profiles, using the measured 11 cm/year infiltration rate. Combined with the data from the mid-core depth (2.2 meters), taken as representative, the calcite deposition rate into the sediment was found to be 22 grams atmospheric CO_2 per year per cubic meter of sediment [37]. We assume a 6 meters global

average depth of root respiration in drylands USZ; even though tree roots extend downwards to much greater depths in drylands compared to temperate zones [43]. The estimated global sequestration rate in the estimated 4.5 million km² is then $6 \times 4.5 \times 10^{12} \times 22 = 0.59 \times 10^{15}$ gram per year or ~0.6 Pg yr⁻¹, ~0.6 billion metric tons per year, or 132 g m⁻² yr⁻¹. We reiterate that the precipitated calcite is very stable in low rainfall drylands regions. In Section 6 below, we describe for 4.5 million km², that an additional 0.4 billion tons of CO_2 per year could potentially be precipitated each year in the soil as calcite, as a result of microbial activity.

5. CO₂ Gas Phase Within the USZ

Although drylands areas have been rather neglected in global carbon budgeting, Refs. [44] and [45] note that these regions have strong downward CO_2 fluxes. The increased depth of the root systems in drylands [43] allows for deeper penetration of the atmospheric CO_2 into the soil profile by root discharge as well as by the creation of physical channels to facilitate gaseous flow into the soil. This increased CO_2 discharge [46] facilitates more rapid weathering of the underlying lithology and the minerals within the soils. The soil CO_2 gas can reach partial pressures that are one to two orders of magnitude over the ambient atmospheric partial pressure [34,36]. The chemical weathering of rocks converts soil CO_2 into dissolved inorganic carbon (DIC), mainly bicarbonate (HCO_3^-). This then descends into the water table or precipitates within the USZ as calcite.

Consider the weathering of silicate rocks, using the calcium form of plagioclase:

$$Ca_2Al_2Si_2O_8 + 2CO_2 + 3H_2O \rightarrow 2Ca^{+2} + Al_2Si_2O_5(OH)_4 + 2HCO_3^- \tag{5}$$
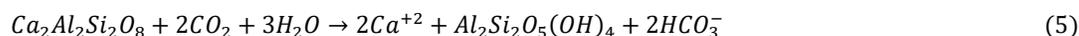
All of the HCO_3^- formed and released in solutions come from atmospheric CO_2. Likewise, for carbonate rock, the enhanced weathering through enriched CO_2 in the recharge facilitates the transformation of atmospherically derived CO_2 into DIC, by dissolution of limestone:

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca^{+2} + 2HCO_3^- \tag{6}$$
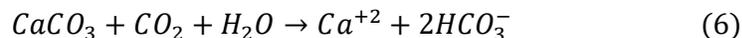
In Eqs. 5 and 6, contemporary and past weathering of rocks has converted atmospheric CO_2 into DIC. Initially dilute rainwater recharge, containing exceedingly small amounts of DIC [47], dissolves atmospherically derived CO_2 from the soil, and then incorporates it as DIC as the recharge descends through the USZ. Depending upon such factors as host rock and water pH, the bicarbonate can range normally from 25 to 400 ppm [48]. In the USA, an average of eight aquifers yielded what was a representative bicarbonate value for groundwaters of 190 mg/L of HCO_3^- [49]. In Israel, the ground water so charged contains 146-225 mg/L of HCO_3^- for the generally minor basalt aquifers [50]; while the major groundwater resources within the carbonate rich host rocks average roughly 270 ± 40 mg/L of HCO_3^-, or more than 0.25 g HCO_3^- per liter. Once the transported HCO_3^- reaches the water table, the CO_2 is stored long term. Analysis of the isotopic composition of carbon in bicarbonate reveals the source of CO_2. The $\delta^{13}C$ of the HCO_3^- in modern groundwater falls in the range of −9‰ (PDB) to −13‰ (PDB), with a preponderance of the measurements falling towards the middle of the range [24,51]. The $\delta^{13}C$ of the root exhaled CO_2 from C3 plants [52] that dissolves in the soil moisture is approximately −22‰ (PDB). Thus, approximately half of the total DIC, ~0.1g per liter, is derived from atmospheric CO_2; while the remainder comes from dissolution of old limestone and dolomites. Once within the aquifer, the water chemistry remains generally stable. Consequently, aquifer water under drylands forests may also be considered a vast sink of atmospheric CO_2. Ref. [53] 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 chronological controls are weak, so that the recharge rates of these aquifer waters and their flow rates are poorly constrained. Thus, we cannot reliably estimate the annual rate of bicarbonate injection into the aquifers under afforested semi-arid lands. This factor though should be kept in mind as contributing to the positive effects of afforestation as it pertains to inorganic CO_2 sequestration, particularly when better hydrological controls become available. An estimate of the modern total global flux of atmospheric derived CO_2 into groundwater

as DIC has been calculated to be ~0.2 Pg carbon per year [54]. This component, though large, is not included quantitatively in our estimate of inorganic carbon sequestration, for it was not specific to drylands nor to forestation.

6. Microbial Sequestration of Atmospheric CO2 as Inorganic Carbon

Soil microbes have long been known to precipitate calcites [55]. The diverse and intricate biochemical pathways through which soil microorganisms utilize atmospheric CO_2 to precipitate calcite have been thoroughly documented [56,57]. Ref. [58] noted that microbial abstraction of atmospheric CO_2 can be long-term and inexpensive. More recently, Ref. [59] demonstrated experimentally under laboratory conditions that desert microbes have the genetic ability to use atmospheric CO_2 to form insoluble calcite precipitates. Under optimal laboratory conditions, they found that calcite precipitates at a rate of 52 μg C per kg of soil per day; corresponding to ~84 g CO_2 m^{-3} yr^{-1}, assuming a soil density of 1.2 g cm^{-3}. This is about 4 times higher than the 22 g CO_2 m^{-3} yr^{-1} inorganic sequestration rate described in Section 4. However, the effective thickness within the soil column is much smaller in a young forest. Field studies by Ref. [60] have verified that dryland farm soils harbor such microbes.

The major factors inhibiting microbial activity and calcite precipitation are the intense UV irradiation of the soils (top ~10 cm), lack of soil moisture (top ~20 cm) and lack of soil organic carbon in drylands [61]. Drylands forestation with the accompanying improvement in soil nutrition and moisture may significantly revive drylands soil microbiological activity to depths of 1 or more meters [62,63]. Soil microbes, including bacteria and fungi, play a vital role in breaking down organic matter, such as dead trees and leaves. The decomposition processes release CO_2 into the soil. The CO_2 dissolves in soil water to form HCO_3^- which then combines with Ca^{2+} to eventually precipitate as calcite within the soil column. The calcium ions originate from the weathering of rocks, soil minerals, and the release of Ca^{2-} from clays.

In a mature forest ecosystem, microbial activity and calcite precipitation would occur at those depths characterized by the presence of deep roots, organic matter accumulation, and stable moisture conditions. Depending on specific forest conditions, significant microbial activity may therefore be found at depths of 1 meter or more. Ref. [64] demonstrated that forestation contributes nutrient carbon to the soil, which may stimulate microbial activity to a depth of several meters. Unfortunately, representative soil profiles in drylands forests showing the concentration of calcite precipitating microbes are not available. Nonetheless, assuming a soil depth to 1 meter and ~84 g CO_2 m^{-3} yr^{-1} in 4.5 million km^2, corresponding to ~84 g CO_2 m^{-2} yr^{-1}, the soil microbial activity would potentially sequester an additional 0.4 billion tons of CO_2 per year ($4.5 \times 10^{12} \times 84 = 0.38 \times 10^{15}$ g) in the soil as calcite. It is possible that over time, the microbial communities will increase in mass, and descend through the soil profile to greater depth. Thereby, the microbial contribution would increase proportionally.

Including the 0.6 billion tons estimated inorganic carbon sequestration per year of Section 4, we therefore assume the drylands inorganic sequestration rate to be ~1.0 Pg CO_2 yr^{-1}. This is ~40% of the 550 grams organic CO_2 m^{-2} yr^{-1} determined by Ref. [20] at Yatir forest. Thus, there are two forestation processes that act to sequester atmospheric CO_2 as inorganic carbon.

7. Water Under the Harshest of Deserts

It is precisely under the harshest drylands that water can be economically found for afforestation. Across North Africa, there are extensive extant water reserves in fossil groundwater. These can be found in areas where there is virtually no effective recharge today, such as under the Sahara Desert. The Nubian Sandstone Aquifer System is the largest of these, with an aerial extent exceeding 2 million km^2 under the Sahara, extending under Egypt, Libya, Chad and Sudan. The total amount of freshwater in the aquifer is estimated as ~370 thousand km^3 [65]. The latest major recharge of this aquifer was ~128 thousand years ago [66]. The aquifer has correlative stratigraphic sections with concomitantly large water reserves under central Sinai, the Negev desert in Israel, parts of

Jordan and Arabia. The Continental Intercalaire aquifer [67] situated under Algeria and Tunisia has an area of 600,000 km², while its shallower associated Complexe Terminal aquifer covers 35,000 km² in Tunisia [67,68]. In the Arabian Peninsula, some of the driest deserts in the world sit atop large groundwater reserves. The Mega Aquifer System is one of these. It underlies Saudi Arabia, Iraq, Jordan, Yemen, Oman and the United Arab Emirates for 2 million km² [69]. The Saq aquifer (560,000 km²) is another extensive reservoir of paleowater residing under the desert shared by Saudi Arabia and Jordan [70,71]. In southern Africa, the 900,000 km² aquifers underlying the Kalahari Desert [72] contain waters that are thousands of years old [73,74]. The arid to semi-arid Karoo basin (200,000 km²) is underlain by old groundwater resources as well [75]. In Australia, the Great Artesian Basin extends for 1.7 million km², underlying desert to semi-arid regions. It contains an estimated 65 thousand km³ of water [76,77]. These are paleowaters of generally good quality [78,79]. In North America, large and very old water reserves reside in semi-arid regions. These include the Milk River Aquifer, running 25 thousand km² beneath semi-arid Alberta, Canada and Montana, USA [80]. Aquifers of similar size, often nested adjacent to each other or stacked one upon the next, are found extending from Louisiana to the Mexican border. These include the Trinity aquifer, the Pecos Valley aquifer, the Hosston aquifer, the Carizzo and Wilcox aquifers, and the Gulf Coast Aquifer (Texas Water Development Board 2016). These contain extensive quantities of paleowater [81], presently underlying rather treeless drylands. They all show little or no surface expression as to their true potential to sustain long-term forestation. The above is not a complete list of such desert aquifers. They demonstrate that there are much larger land areas with a concomitant local water supply that are available for afforestation than had been previously assumed [12,13]. Indeed, paleowater filled aquifers can be found in semi-arid and arid areas on all the inhabitable continents [82]. Due to the low population densities and inhospitable climate, the hydrology and ages of the waters in many such aquifers underlying deserts globally have not been fully investigated.

8. Contaminants in Surface and Groundwater That Would Restrict Their Use Only to Afforestation

Note that although the waters in several of the fossil aquifers have contaminants that make them inappropriate for domestic or animal husbandry purposes, they are nonetheless well suited for planting trees. For example, waters in the phreatic aquifers of the western Kalahari are marked by high nitrate values, well above maximal permissible human health levels, as observed in 18% of the measured wells [73]. However, no adverse effects would accrue to trees irrigated with this water. A more egregious example is the soluble radium contamination, found above maximal permissible levels for human consumption, within the water of the huge Nubian Sandstone Aquifer System; as well as its correlative extensions across the northern Sinai and into the Negev desert [83,84]. Elevated levels of this pernicious radioelement have also been encountered locally in the fossil waters of the extensive Saq aquifer, the principal water supply of Saudi Arabia [85]. Yet, these waters could be used in wide-scale afforestation efforts [86]. The reason is that desert plants have developed biochemical barriers to non-nutrients, resulting in small soil to plant Transfer Coefficients [87]. Arsenic, a known carcinogen, is another contaminant that would preclude the use of such water for domestic purposes or for food production. The large (176,000 km²) Indus River Valley of Pakistan could be another potential area for extensive afforestation. This valley would be a harsh desert were it not for the Indus River that flows through it. The river gains its fresh water from the melt of glaciers in the mountains at its source. This densely populated, economically vital area is dependent upon the river waters for irrigation, for its fish industry, and for growing diverse agricultural crops. Unfortunately, the waters and the soils of the young underlying phreatic aquifer are naturally polluted with arsenic [88]. The arsenic is transferred to its agricultural produce as well as bio-accumulated in the fish [89]. Arsenic incorporated into the diet of the inhabitants [90] is slowly poisoning them. Trees would not suffer from these arsenic levels, as would humans and their livestock. This otherwise arid area may best use the extensive available but contaminated water for afforestation projects.

9. Sustainability of Afforestation

To what extent can afforested trees successfully grow in harsh arid environments, even if water is supplied? A very high mortality was noted for example, ranging from 20-80%, depending upon the species, for reforested seedlings in Anatolia, Turkey [91]. Ref. [63] described how to avoid high mortality rates. They suggest using trees that are known to be adapted to the local environment. There are many species that would be suitable, particularly as underlying fossil waters would obviate the need to be dependent solely on rainfall. Many can thrive on marginal soils, while at the same time improving soil properties, particularly with increases in soil organic matter, soil carbon and nitrogen. Some of the following trees can be successfully planted in arid zones. The deep-rooted species of the Tamarix and the Acacia families (both have roots that can extend to depths in excess of 30 m). These two and the desert willow (*Chilopsis linearis*) are hardy desert plants. The mesquite trees (*Prosopsis*) have even deeper tap roots (up to 50 m). The deep rooting zone would facilitate deep CO_2 penetration for weathering and inorganic carbon sequestration as discussed above. Afforestation can stabilize soil and prevent erosion, offer food for wildlife, and enrich soil with nitrogen. They can also provide high value crops. These would include the Physic Nut (*Jatroph curcas*), which has extensive medicinal uses, the Jojoba (*Simmondsia chinensis*) for its pharmacological and industrial oils; and the Moringa (*Moringa oleifera*) used as a nutrient supplement and for its antioxidant and anti-inflammatory properties. The palm (*Phoenix dactyliferia*), when irrigated, have been profitably planted in dense groves in hyper-arid regions of Israel to provide high quality dates for export [43,92–94]. Thus, if groundwater is available, the arid and hyper-arid regions should not be dismissed for their afforestation potential. In this regard, previous afforestation models that increased the area of total drylands available for afforestation to 15% [19] or to 25% [18] should merit reconsideration. We assume that a drylands area of 9 million km² (20%) is feasible for afforestation.

One proposed reforestation method will require manpower efforts by local farmers, but not large financial investments. This method is known as FMNR, Farmer Managed Natural Regeneration [95–97]. FMNR is a sustainable land management practice developed by environmental conservationist Tony Renaudo that empowers local farmers to restore and manage trees by nurturing existing root systems and promoting natural regeneration. It fosters the regrowth of native trees that have been cut down or damaged. Ref. [96] has reviewed worldwide FMNR activities. The below ground root system, which comprises a significant fraction of the organic carbon, has been previously been assumed to die off, to decompose, to begin returning its stored carbon to the soil and atmosphere. However, the roots do not necessarily die off quickly. Even in harsh, desert-like conditions, the root systems of many felled trees remain alive, comprising "underground forests". Tree stumps, supported by their live roots, often spontaneously grow new sprouts. Usually, without human intervention, only a small bush develops. However, by carefully pruning and protecting new sprouts, selecting the tallest and strongest ones, a new tree can grow quickly. FMNR is applicable in the world's drylands, where it can enhance soil fertility, improve moisture retention, reduce erosion, and promote the regeneration of native trees. It has already transformed millions of hectares of degraded land in at least 29 countries. A significant portion of the world's drylands is certainly suitable for forest regeneration. Following forest regeneration, carbon sequestration is renewed.

FMNR has demonstrated that drylands are suitable for both forestation and agriculture. Moreover, it has been found that the mixing of forests with agriculture is mutually beneficial. The same forested area can grow both trees and agricultural food products. The trees provide shade protection, preserve soil moisture, provide soil stability, increase biodiversity, provide lumber and improve agricultural productivity. The agricultural activity in turn provides fertilizer to the trees.

10. Dryland Carbon Sequestration Cooling and Albedo Reduction Reassessed

The sustainable area for potential global sequestration of atmospheric CO_2 by drylands forestation can be conservatively doubled to 9.0 million km² with respect to the area considered suitable by Ref. [12]. Based on this larger area, we make a new assessment as to how much CO_2 can be removed from the

atmosphere and stored by dryland afforestation. We obtain a potential total sequestration rate of ~7.0 billion tons CO_2 yr^{-1}. This rate would correspond to a significant 35% of the annual increase of 20 billion tons of CO_2 presently being added to the global atmospheric CO_2 reservoir of ~3200 billion tons. It can be directly applied to attenuating the rate of ocean acidification. However, the desired global cooling effect by atmospheric CO_2 reduction would be partially offset by the expected reduction in a forest's land surface albedo. The reason is that the albedo (reflectivity) of the incident solar radiation on dark forests would be reduced (leading to a warmer surface) compared to the pre-forestation, higher albedo, cooler desert surface. The effect of the change in land surface albedo has been known for some time to affect land surface temperatures, which in turn could significantly affect precipitation both locally and over extended distances [98,99]. Many investigations have been carried out recently on the effects of forest albedo as it pertains to global warming [12,14,100–102]. The impact of albedo is nuanced. Ref. [103] contends that forests are not only a product of their environment, but also modulate climate itself. For example, forests release biogenic, volatile organic compounds which are important in forming nuclides of raindrops, cloud formation, and the enhancement of cloud reflectivity. This ultimately can lead to the formation of low-lying dense clouds over the forest, which would inhibit the penetration of short-wave solar radiation. Forest evapotranspiration cools while supplying humidity to the environment. The trees add roughness to the landscapes, which results in a turbulent air flow aiding in the dissipation of surface energy and daytime cooling (relative to non-forested ground). Ref. [104] noted that the loss of forested land can lead to changes in temperature values that range from a net warming to a net cooling.

Ref. [16] studied albedo variables such as tree species and forest age in a wide scale study of forests spanning across the whole USA. On average, they found that albedo has offset almost 50% of the cooling benefit attributable to carbon sequestration. They found more specifically that the land surface albedo of a forest is strongly affected by both tree species and age. Such albedo changes are due to differences in leaf/foliage color and thickness properties, canopy structure, growth patterns, and surface reflectivity; specific to how different tree species change as they mature. For example, for Lodgepole pine forests, they found a decreased carbon storage benefit of ~40% in young (10 years) forests; while the sequestration benefit diminishes completely after 100 years. Of course, global warming needs to be addressed over a 10 year time scale before considering what happens after 100 years. More studies are certainly needed of the albedo effect, to help choose the optimal trees for different global forests.

For a 7.0 Gt yr^{-1} total rate, due to the decreased albedo, the total CO_2 "equivalent" atmospheric cooling sequestration rate would be reduced to 5.0 Gt yr^{-1} [12]. This value would still correspond to a significant 25% of the annual increase of 20 billion tons of CO_2 presently accumulating in the global atmosphere. Again, this is a preliminary and rough estimate. But it justifies extending the afforestation potential into the arid and hyper-arid lands. Ref. [105] advanced the idea that afforestation affects ecology in a dynamic way. Using and irrigating the land will influence the local ecology by increasing soil moisture. The trees would add organic matter to the soil, carbon and nitrogen, which in turn beneficially affects the microbial populations. The evaporation of water not only has a local cooling effect [106]; but combined with evapotranspiration, the moisture may stimulate cloud formation. The resulting dense low-lying clouds, which are strongly coupled to the ground, would reflect solar radiation. This would increase the effective albedo and thus contribute to cooling of the land, notwithstanding lost reflectivity. The added moisture in turn may eventually spur increased precipitation. Estimating more precise effective sequestration rates would require considering the choice of tree species, stand densities, canopy cover, precipitation levels, cloud cover; and how CO_2 concentrations equilibrate between atmosphere, forested drylands and oceans. Suffice it to say that afforested lands may, over time, increase their sequestration potential vis a vis atmospheric CO_2, while extending the forests' natural ranges.

11. Limitations

Our global sequestration estimate is based on measurements at a single location, on which basis we extrapolate to the entire planet. The validity of the extrapolation depends therefore on how representative Yatir forest is of the global drylands. With an aridity index AI = 0.18, drier and hotter than most of the world's semi-arid regions (AI = 0.2-0.5), it is nonetheless healthy and productive without irrigation or fertilization. Therefore, its sequestration rate is likely lower than the average drylands rate. We cautiously estimate that our global extrapolation serves as a minimum threshold, with the possibility of the rate being higher.

Certainly, taking, including, and averaging data from other drylands forests in varied geographical locations would be more representative. One should include forests covering the full range of drylands aridity indices, as well as having a variety of topographic conditions such as slope or soil type or soil thickness. Since this was beyond the scope of the current study, our estimated global sequestration rate is only tentative. Our objective is not to give a definitive result, but rather to generate interest such that other research groups may be motivated to provide complementary data and to thereby refine our initial rough estimate.

Throughout, we have used an estimated albedo effect sequestration reduction in a 4.5 million km^2 drylands area of 1 Gt CO_2 per year [12]. This value warrants further study and may be revised accordingly.

The extrapolation we present is based on a planted Aleppo Pine (*Pinus halepensis*) forest. After such a forest reaches equilibrium, the quantity of organic carbon fixed by photosynthesis will be approximately equal to the quantity released. The release takes place via decay of fallen trees and litter, natural and human initiated fires, harvesting of forest products, and respiration of CO_2 as trees convert stored carbohydrates into energy. Overall, these processes represent the dynamic balance of carbon cycling within a mature forest. We emphasize here that the positive sequestration rate of organic carbon from tree growth is valid only during the first 50-100 years of the forest's life until it reaches equilibrium. The actual time for planted forests in general would depend on the tree type and specific management practices and environmental conditions. By contrast, over the entire lifetime of the forest, including after equilibration, there is a continuous increase in the inorganic carbon sequestration that is permanently fixed in the form of calcite.

12. Conclusions

Global drylands offer extensive area for afforestation efforts aimed at reducing global warming and oceanic acidity by removing atmospheric CO_2 through the combination of inorganic and organic carbon sequestration. Our estimate of the potential quantity of sequestered CO_2 offers optimism for the efficacy of the project, yet should be considered both conservative and tentative. Several parameters related to inorganic sequestration for example are not well constrained at present. These involve microbial calcite precipitation rates, and the sequestration of atmospheric CO_2 in the form of bicarbonates in underlying aquifers.

We nevertheless estimate the potential for significant long-term removal of atmospheric CO_2 via carbon sequestration in global drylands forests. Our estimate is based on measurements in the planted semi-arid Yatir forest in Israel. This forest sequesters ~550 g CO_2 m^{-2} yr^{-1} as organic carbon in the trees' biomass and an estimated ~216 g CO_2 m^{-2} yr^{-1} as inorganic carbon precipitated as stable calcite ($CaCO_3$) in the forests' soils.

The potential maximal efficacy of global forestation for reducing global warming and ocean acidification depends on the maximal area available for sustainable forestation. The dominant limitation in global drylands regions is the apparent lack of sufficient water. Published evaluations ostensibly restrict the potential drylands surface available for sustainable forestation to ~4.5 million km^2, only ~10% of the global drylands. However, immediately underlying many drylands, plentiful groundwater is available. These are paleowaters (fossil waters) that have recharged underlying aquifers during prior wetter climatic regimes. Conservatively, taking these fossil waters into account, we estimate that an area of at least ~9.0 million km^2 would be available for drylands afforestation.

This would yield a potential total annual sequestration rate of at least ~7.0 Gt CO_2 yr^{-1}, divided between 5.0 Gt CO_2 yr^{-1} (organic) and 2.0 Gt CO_2 yr^{-1} (inorganic). This amount represents a respectable ~35% of the annual rate of atmospheric CO_2 increase.

However, the cooling effect through removing the CO_2 greenhouse gas is more nuanced, as these forests would alter surface energy dynamics. The transformation of bright high albedo (reflectivity) drylands to darker forests could reduce the positive projected climate cooling significantly for the mass of greenhouse gas removed from the atmosphere. Considering only the reduced land surface albedo, the effective cooling sequestration rate may be closer to ~5.0 Gt CO_2 yr^{-1}. However, some positive atmospheric feedback mechanisms may oppose this reduced albedo cooling. For example, increased forest evapotranspiration may decrease surface temperature and increase cloud formation. The species and age of the trees as well as the canopy height may mitigate the heating effects of reduced albedo. And thick, low lying stratocumulus clouds would tend to decrease heating by incident solar short-wave radiation.

All things considered, drylands forestation comprises a more cost-effective, long-term use of drylands and fossil water when considering cooling benefits; relative to the current profligate, agricultural exploitive draining of these fossil aquifers. A signal case in point is the hydrologic situation in the Ogallala or High Plains paleo-aquifer, covering 450 thousand km^2 of the central semi-arid USA [107,108]. Present use combined with past uncontrolled exploitation and waste has seriously depleted this aquifer [109,110]. Similar examples of excessive use of fossil water has been taking place in Saudi Arabia [111], Arizona [112], Yemen [113] and Ethiopia [114]. Therefore, we suggest that these ongoing agricultural practices should be curtailed; and new, less water-intensive ways of utilizing the aquifers should be initiated. Significantly, planted drylands forests require roughly 50% less water (or even no irrigated water as in the Yatir forest) compared to more water intensive agricultural growing of fruits or vegetables. Forestation should have priority in all drylands areas where paleo-aquifers are the dominant water supply.

To date, drylands 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 drylands regions. Far from being a drawback, this gives added economic potential to these marginal regions. Besides, in addition to sequestering carbon, semi-arid forests provide important ancillary environmental functions. These include preventing encroaching desertification, producing oxygen, increasing precipitation [100], 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. Considering all these advantages, one may expect widespread social acceptance by the local population; this being an important requirement for the success of the project.

FMNR, Farmer Managed Natural Regeneration, may foster the regrowth of native trees in deforested drylands. The root systems of many felled trees remain alive, comprising "underground forests". Tree stumps often spontaneously grow new sprouts. By carefully pruning and protecting new sprouts, new trees can grow quickly in a significant portion of the world's drylands. Following forest regeneration, carbon sequestration would be renewed. FMNR may also possibly be applied in areas where trees have been burned in forest fires, both in drylands and temperate regions. Fires that spread quickly by heavy winds may, for example, be more heat damaged around the canopy compared to near ground level. In such cases, cutting selected burned trees at about 0.5 meter above the ground may promote the regeneration of sprouts from the remaining trunk, particularly if the root system is intact. This approach would be especially effective for tree species that are resilient to fire. Additionally, deforested temperate areas may also be appropriate for FMNR, especially if the soil remains fertile and remnants of tree roots are still present to support regeneration. Expanding on these subjects is beyond the scope of the present study.

With the availability of fossil water and the judicious choice of trees adapted to aridity, the drylands regions of the planet should be the prime focus for global forestation efforts. Sequestration of atmospheric CO_2 would also reduce the rate at which oceanic acidification is occurring. Overall, our estimate demonstrates the global potential for drylands forests to develop into significant carbon sinks. Note, however, that a significant additional area of potential global forest dryland—on the order of millions of square kilometers—may be available for FMNR reforestation [95–97], beyond the 9 million square kilometers used in the CO_2 sequestration calculations above. Thus, the 9 million square kilometers included in our sequestration estimate should be considered a conservative value. We emphasize the need for further drylands forest sequestration measurements, and the need to begin implementing a global land management policy of widespread afforestation and reforestation regeneration in drylands regions.

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