

Article

Breathing Planet Earth: Analysis of Keeling's Data on CO₂ and O₂ with Respiratory Quotient (RQ), Part II: Energy-Based Global RQ and CO₂ Budget

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[†] The research topic was conceived and work was carried out solely by the author after learning of Keeling's curves on CO₂ and O₂ in atm.

Abstract: For breathing humans, the respiratory quotient (RQ = CO₂ moles released/O₂ moles consumed) ranges from 0.7 to 1.0. In Part I, the literature on the RQ was reviewed and Keeling's data on atmospheric CO₂ and O₂ concentrations (1991–2018) were used in the estimation of the global RQ as 0.47. A new interpretation of RQ_{Glob} is provided in Part II by treating the planet as a "Hypothetical Biological system (HBS)". The CO₂ and O₂ balance equations are adopted for estimating (i) energy-based RQ_{Glob(En)} and (ii) the CO₂ distribution in GT/year and % of CO₂ captured by the atmosphere, land, and ocean. The key findings are as follows: (i) The RQ_{Glob(En)} is estimated as 0.35 and is relatively constant from 1991 to 2020. The use of RQ_{Glob(En)} enables the estimation of CO₂ added to the atmosphere from the knowledge of annual fossil fuel (FF) energy data; (ii) The RQ method for the CO₂ budget is validated by comparing the annual CO₂ distribution results with results from more detailed models; (iii) Explicit relations are presented for CO₂ sink in the atmosphere, land, and ocean biomasses, and storage in ocean water from the knowledge of curve fit constants of Keeling's curves and the RQ of FF and biomasses; (iv) The rate of global average temperature rise (0.27 °C/decade) is predicted using RQ_{Glob(En)} and the annual energy release rate and compared with the literature data; and (v) Earth's mass loss in GT and O₂ in the atmosphere are predicted by extrapolating the curve fit to the year 3700. The effect of RQ_{Glob} and RQ_{FF} on the econometry and policy issues is briefly discussed.

Keywords: respiratory quotient (RQ); fossil fuels; carbon budget; global RQ; Earth's mass loss



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1. Introduction

Atmospheric oxygen production on Earth started about 3.2 billion years ago. The total O₂ produced was estimated at 5.63×10^5 Peta moles with 0.375×10^5 Peta moles as free oxygen in the atmosphere, 310 Peta moles as dissolved oxygen in the ocean, and the remainder stored in oxidized form (CH₂O, SiO₂, H₂O, CaCO₃, etc.) as terrestrial and oceanic compounds [1]. Thanks to abundant oxygen, biological species which consume oxygen evolved on Earth. Generally, the biological systems (BSs) include humans, plants and trees, phytoplankton (PP), etc. The plants, trees and PP are generally referred to as biomasses and perform both (i) respiration, which consumes almost 50% of C(s) produced via the photosynthesis process [2], and (ii) production of oxygen. But humans perform only respiration without the production of oxygen. In biology, the respiratory quotient (RQ) is defined as the ratio of CO₂ moles released to the moles of oxygen consumed. The RQ estimated via nasal intake and vented exhaust is called the Apparent Respiration Quotient (ARQ) [3], which could be different from the values of RQ estimated with a chemical formula of nutrients used for metabolism.

The CO₂ growth rate in the atmosphere is affected by CO₂ released from the combustion of FF and by natural CO₂ sinks in the ocean and the land in the carbon cycle.

The energy demand is driven by the choice by consumers, level of industrialization and urbanization, climate and environmental policies of the nation, and available technology. There are three reservoirs for storing anthropogenic CO₂ over several decades: atmosphere, land (terrestrial biosphere), and oceans {about 93% of C(s)} [4]. The O₂ concentration in the atmosphere is affected by the consumption of O₂ by FF and O₂ production. Hence, Keeling's data on CO₂ and O₂ in the atmosphere (1991–2021) are affected by human activities and the distribution of CO₂ sink by land and ocean, revealing the inverse relation between CO₂ and O₂ in a periodic saw tooth pattern within each year.

While part I dealt with review of RQ and estimation of global RQ, the RQ concept, along with CO₂ and O₂ balance equations, is used in Part II to (i) estimate global CO₂ sink and O₂ production by land and ocean biomasses, (ii) determine storage of CO₂ by the oceans, (iii) establish the control groups that affect the CO₂ growth in the atmosphere, and (iv) present the fossil energy-based RQ_{Glob,(En)} relation, which enables a ready estimation of CO₂ added to the atmosphere from the data on annual fossil energy consumption.

2. Literature Review

The global carbon cycle is affected by the release of CO₂ from FF and the exchange of O₂ and CO₂ between the atmosphere–land and atmosphere–ocean interfaces [5]. A detailed review of CO₂ sources and sinks and O₂ sinks and sources, and a comparison of terminologies between photosynthesis, engineering, and biology literature are presented in Part I. A brief literature review pertinent to Part II is presented here: (i) effects of CO₂ sources other than those from FF and land use (LU) on the estimation of RQ based on annual CO₂ and energy data, (ii) controversy on % O₂ contribution by ocean biomass to the atmosphere, and (iii) the relation between global warming or “planet fever,” and the Paris agreement to limit temperature rise and the annual energy release rate.

2.1. CO₂ Sources and O₂ Sinks

The development of modern industrialized nations across the globe resulted in an increase in CO₂ from a pre-industrial level of 285 ppm (1850) to 380 ppm in 2006 and 414 ppm in 2020 [6]. In addition to CO₂, the greenhouse gases (GHG) include CH₄, N₂O, O₃, etc. Even though the ozone is a GHG, the beneficial effect of stratospheric ozone is more important than its contribution to global warming. An average person in the USA releases 16 tons of CO₂e (which includes all GHG), while the global average per person is 4 tons. The US EPA report presents the % GHG distribution from the transportation and energy industry, constituting almost 50% of total GHG (Excel table in [7]). CO₂ from land use (LU) accounted for 33% around 1750 [8], while currently, FF: 87%, and LU: 13%. In addition to CO₂ sources from the combustion of FF in thermal power systems and LU, cement production results in additional CO₂ release. About 50% of cement CO₂ is produced by the following process:



while 40% is obtained from the CCP (Coal Combustion Product). The net CO₂ released in 2021 for cement is estimated to be 2.4 GT while FF energy is 36.3 GT, and hence, the cement CO₂ is about 6.6%. Thus, RQ based on global CO₂ and annual energy consumption data yields RQ_{FF+LU+cement} due to the addition of cement CO₂ [9]. There is no O₂ sink in cement manufacturing, while there is an O₂ sink in the oxidation of fuels to CO₂. Deforestation also causes deoxygenation. The oxygen sinks cause decreasing O₂ concentration in the atmosphere [10,11]. Based on the parabolic model [11,12] for O₂ concentration in the atmosphere, Martin et al. found that the O₂ in the atmosphere will decrease by 50% (i.e., O₂ concentration: 10.5%) by the year 3600. The atmospheric hypoxia will result in human extinction. This result is in close agreement with results from Part I which state that the O₂ concentration will reach 16.5% by the year 3700 when a quadratic curve fit (also known as a parabolic fit) is used for Keeling's data on O₂ concentration in the atmosphere.

2.2. CO₂ Sinks and O₂ Sources

Between 1991 and 2020, CO₂ increased by 17% (from 354 ppm in 1991 to 41 ppm in 2020), and photosynthesis grew by 12% from 1982 to 2020 [13] due to CO₂ fertilization and is expected to increase by 52% in the 21st century. However, the increased global temperature has a negative effect on photosynthesis. Just like biomass growth requires the consumption of C, growing humans from 3.2 kg (7 lb.) to 34 kg (75 lb.) also requires the storage of C, which becomes fossilized if buried or results in release of CO₂ if cremated. Assuming the mass % of C in the human body is at about 18.5% (wet human: 60% moisture and 40% dry mass, dry UCF: CH_{2.10}N_{0.15}O_{0.48} Ca_{0.024} P_{0.021}; see Part I) [14], the C storage rate within humans (about 1.5 million tons/year assuming human mass of 75 kg, life span of 75 years and world population of 8 billions) is negligible compared to the C storage in biomass (order of GT/year).

2.3. Ocean CO₂ Sinks and Ocean O₂ Sources

The oceans occupy 70% of Earth's area but only 1% of the biomass, whereas land occupies 30% of Earth's area but contains 86% of the biomass. About 80% of the ocean water biomass is composed of animals, protists, and bacteria [15]. About 78% of global animals live in the ocean. Though the C in phytoplankton in the oceans amounts to only ~1–2% of the total global biomass carbon, they serve as a C sink of 30–40% of total C [16,17].

The ocean CO₂ sink works two ways. The CO₂ from high Pa_{CO2} in the atmosphere diffuses to water, dissolves, and is transported to deep water (physical process, shorter time scale). The second way is to use CO₂ near the ocean surface to grow PP since sunlight is available (chemical process, longer time scale) [18]. With a net global production of 50 GT of O₂/year, RQ = 1, it accounts for 50% of the oxygen, though it is only ~1% of global plant biomass [19]. Blue C populations (seaweed, green, red, and brown algae) are almost nine times that of land plants. Phytoplankton consume about 36.5 GT of CO₂ (or 10 GT of C(s)/year) annually. The PP also serves as an aquatic food web (e.g., zooplankton, including bacteria, fungi, etc., along with dead plants and other animal material; they are consumed by fish). The energy needs of marine animals result in the consumption of most O₂ produced by ocean biomass and the release of CO₂.

However, there is controversy about the net amount of O₂ transferred from the ocean to the atmosphere after marine organic matter (MOM) consumption. The oxygen concentration of 0.001% of the current level has existed for almost two billion years. Then, the photosynthesis by phytoplankton (plants and microscopic ocean bacteria) and trees and plants on land resulted in 21% oxygen today. The marine organisms also require oxygen for respiration/metabolism to convert food to energy, so they consume oxygen produced by PP. The dead PP falls like “marine snow” to the sea floor. This “biological carbon pump” transfers about 10 GT of C/year from the atmosphere to the deep ocean [20]. The dead plants are also oxidized due to deep water circulation. Even though the oceans contributed about 50% of oxygen to the atmosphere over hundreds of millions of years, 50% of the oxygen the BS breathes in does not come from the oceans, since most of the oxygen from the oceans is consumed by MOM. Further, the excess nutrients discharged to lakes and rivers (eutrophication) cause excessive algae boom and low oxygen water [21,22]. Thus, only 1.5 GT /year is outgassed from the oceans [23,24]. The global oxygen balance studies by Huang et al. [25] state that only 1.74 GT/year of oxygen enters the atmosphere from the ocean, while the land biomass produces 16.01 GT/year [25]. A detailed report on ocean deoxygenation cites about 0.8 GT/year as of 2017 but –1.8 GT/year as of 2011 [26].

It is noted that the annual ocean CO₂ storage in Refs. [27,28] deals only with (i) the formation of bicarbonates without the production of O₂ and (ii) dissolved CO₂ [29]. The CO₂ sink by ocean biomass is omitted in the balance equation (Equation (3) of Ref. [27]), presumably assuming the CO₂ sink by phytoplankton is compensated for by CO₂ production from the oxidation of dead plants within the oceans.

The PP concentration varies depending on the latitude, time of year [30], and depth where they grow. Thus, CO₂, O₂, and concentrations are affected by ocean circulation.

Table 1 (adopted from [1]) shows that the total distributions of CO₂, N₂, and O₂ differ from the surface distributions.

Table 1. Fraction of N₂, O₂, CO₂ in air and ocean compartments.

	Air	Ocean Surface	Total Ocean
N ₂	0.78	0.48	0.11
O ₂	0.21	0.36	0.06
CO ₂	0.0004	0.15	0.83

2.4. Global Warming and Temperature

Earth's atmosphere is increasingly becoming warmer due to activities of "dust to dust" human transients undergoing several cycles of life and death [31]; see Ref. [32]. NASA collected data from more than 32,000 weather stations, land, weather balloons, oceans, ships, and buoys [33]. The rate of global temperature rise was 0.08 °C per decade till 1981, and jumped to 0.19 °C per decade for the period 1981–2014 [34,35] and 0.25 °C per decade from 2014 to 2021. Heating occurs due to the greenhouse effects of human-driven processes and waste heat from the long-term use of fossil energy, called the "deep warming" problem [36]. The global temperature is determined by conducting an energy balance between solar energy transmitted via the atmosphere loaded with GHG, energy absorbed by Earth, and heat loss via radiation and reflection into space. All these processes drive Earth's heat sources and sinks out of balance. The waste heat from Earth accumulated 381 ZJ with a heating rate of 0.48 W/m², and 89%, 6%, and 1% of thermal energy is stored in the oceans, land, and the atmosphere, respectively [36]. The imbalance rate has recently increased to 0.76 W/m². The average temperature is now 0.9 °C (1971–2020) higher, and sea surface temperatures (SST) along the eastern coast of North America were found to be "13.8 °C or 24.8 °F higher than the 1981–2011 average" [37,38].

The Sustainable Development Goals (SDGs) were enacted by the United Nations in 2015 (i) to fill the needs of the present without harming the needs of future generations; (ii) to take actions to protect the environment, planet, and natural resources and end poverty by 2030 [39]; and (iii) to mitigate global warming by following the Paris Agreement, which dictates that global warming temperature rise must be limited to 2 °C, or preferably 1.5 °C [37]. The Intergovernmental Panel on Climate Change (IPCC) reports [40] and the Forbes website with a "cartoonist" depiction of climate explain the difference between the consequences faced by humans as a result of 1.5 °C and 2 °C rises. However, even if the temperature rise is limited to pre-industrial levels, nature may not restore the climate due to the hysteresis effect [41]. The increased global temperature causes plants to mature more quickly, thus reducing the period of photosynthesis and affecting the photosynthesis process in ocean biomasses. The warming effect resulted in the decrease in the phytoplankton population by 30% compared to the 1980s. The rising global temperature of Earth due to increasing CO₂ (See Figure 2 of Part I for temperature anomaly, Figure 3 of Part I for global average temperature, [9]) may also reduce the amount of C from the photosynthesis process. Hence, by 2040, CO₂ sink due to biomass growth will be reduced by almost 50% [42]. The higher the ocean temperature, more the dissolved CO₂ and O₂ are released from the ocean, resulting in less oxygen for marine life, the expansion of water, and a higher sea level. It is estimated that the dissolved O₂% in the ocean will decrease by 1 to 7% of the current level by 2100 [43].

2.5. Research Gap

While the RQ of humans is important for nutritional therapy on adjusting CO₂, the RQ of FFs provides an avenue for "FF" therapy to reduce CO₂ release from power plants. The budget analysis using "stand-alone" ocean-biochemical and terrestrial-eco system models for C sink [44] involves extensive computational tools and requires an approximate solution as the initial guess for faster convergence. The RQ-based carbon budget analysis is needed

to (i) obtain explicit solutions for CO₂ distribution to the atmosphere, land, and ocean biomasses and storage by the oceans in terms of the curve fit constants of Keeling's data on CO₂ and O₂, and RQ of FF and biomass, and (ii) present control groups affecting the CO₂ budget. Further, there is wide variation in the contribution of oxygen to the atmosphere by ocean biomasses (ranging from 10 to 80%) due to conflicts in the terminology used, for example, total O₂ produced by the ocean vs. net O₂ contributed by the ocean to the atmosphere. Further, most of the earlier literature data do not present CO₂ sink via ocean water biomass (OWBM), but only CO₂ storage by ocean water as dissolved gas and carbonate, presuming that there is no net O₂ transfer from the ocean to the atmosphere, or CO₂ sink by OWBM, while the current work estimates such a contribution. It is desirable to obtain a simple, albeit approximate, relation relating the rate of temperature rise with global RQ obtained from Keeling's data on CO₂ and O₂ and the annual energy release rate. Currently there is no such relation, probably due to the complexities involved in Earth's energy balance.

2.6. Overview of Part I

A brief overview of results from Part I is presented below:

(i) Respiratory Quotient (RQ):

For the CO₂ source and O₂ sinks, the respiratory quotient (RQ) is defined as

$$RQ_{FF} = \frac{\dot{N}_{CO_2,FF}}{\dot{N}_{O_2,FF}} \text{ or } RQ_{FFLU} = \frac{\dot{N}_{CO_2,FFLU}}{\dot{N}_{O_2,FFLU}} \quad (1)$$

For CO₂ sinks and O₂ sources, the quotient (RQ) (which is the inverse of the photosynthetic quotient, PQ) is defined as follows:

$$RQ_{BM} = \frac{1}{PQ_{BM}} = \frac{\dot{N}_{CO_2,LOWBM}}{\dot{N}_{O_2,LOWBM}} \quad (2)$$

where $\dot{N}_{CO_2,FF}$ represents the CO₂ release rate by FF and $\dot{N}_{CO_2,FFLU}$ represents the CO₂ release rate by both FF and LU.

- (ii) The literature on RQ and its relation to various terminologies in the photosynthesis literature were reviewed.
- (iii) RQ values were presented in tabular form for several FFs and BMs in Part I [9]. They are summarized in graphical form in Figure 1 and plotted as a function of the atom ratio H/C with O/H as a parameter.
- (iv) The RQ concept was applied to fossil fuels (FFs) fired for power plants [45], and the relation between RQ and CO₂ released in GT per Exa J was presented:

$$CO_2, \left(\frac{GT}{ExaJ} \right) = \frac{M_{CO_2}}{HHV_{O_2}} RQ = F_{CO_2EJ} * RQ, F_{CO_2EJ} = \frac{M_{CO_2}}{HHV_{O_2}} \approx 0.1 \quad (3)$$

where $HHV_{O_2} = 448$ Exa J/Peta mole of O₂, and $M_{CO_2} = 44.01$ g/mole or 44.01 GT per Peta mole of CO₂.

- (v) The Keeling's data [46] on CO₂ and O₂ were used to obtain curve fit constants using linear and quadratic fits and present RQ_{Glob} as 0.47 ($=d(CO_2)/dt$ in the atmosphere/ $|d(O_2)/dt|$ in the atmosphere), which is similar to ARQ in biology. Planet Earth behaves like a large BS, releasing 0.47 moles of CO₂ to the atmosphere for every mole of O₂ depleted from the atmosphere. The RQ_{Glob} is much less than the RQ of FFs due to CO₂ sink by biomass and CO₂ storage in the oceans.
- (vi) It was shown that the global RQ_{Glob} is a measure of the acidity of the oceans [9]. The lower the RQ_{Glob} is and the larger the difference between RQ_{FF} and RQ_{Glob} , the greater the acidity of the oceans.

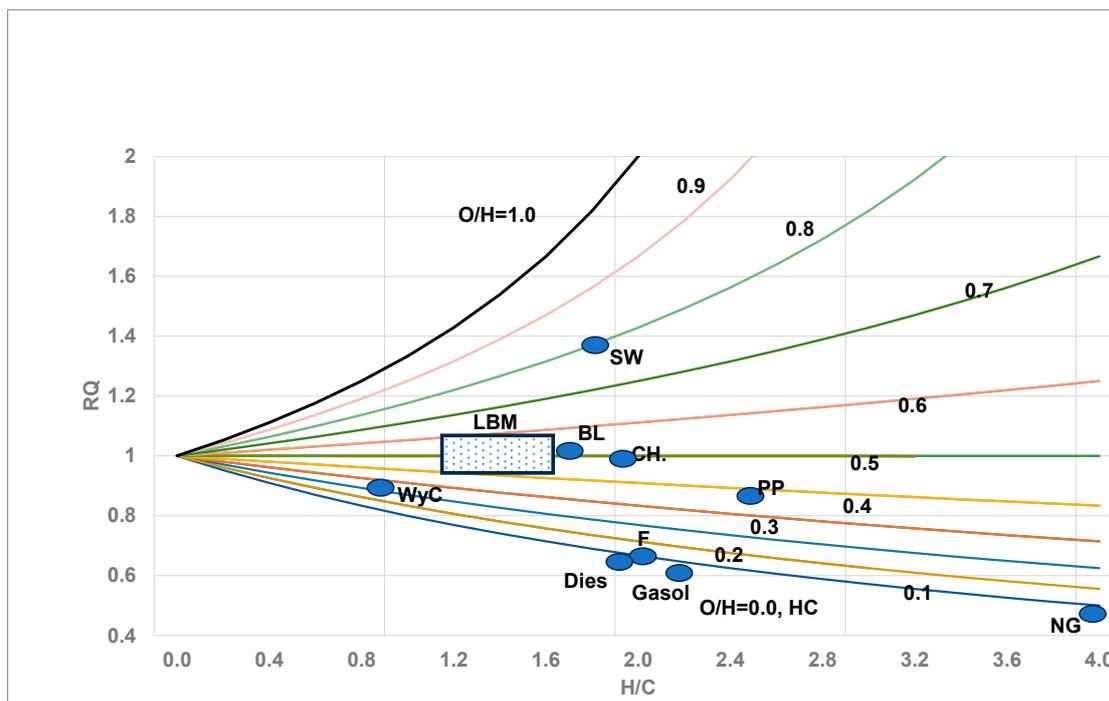


Figure 1. Variation in RQ (CH_hO_o fuel or nutrients with ($h = \text{H/C}$, $o = \text{O/C}$), with O/H as parameter. Generally, $\text{RQ} = 1 / (1 + h/4 - o/2)$ or $1 / [1 + (h/4) * \{1 - 2 * (\text{O/H})\}]$. At $\text{O/H} = 0.5$, $\text{RQ} = 1$. Figure adopted from [47] and modified. Symbols denote RQ estimated from chemical formula of many fuels and nutrients. Most land biomasses have O/H varying from 0.4 (Table A.1 in Appendix of Part I) to 0.57 with an average of 0.49 (see rectangular box labelled LBM), while RQ_{LBM} varies from 0.94 to 1.05 with an average of around 1 due to $\text{O/H} = 0.5$; see horizontal line. It appears as though H_2O molecule is chemically attached to C atom in the BM when $\text{O/H} = 0.5$ and hence, during oxidation, H_2O is detached, O_2 is needed to oxidize only C, and as such, $\text{RQ} = 1$; during growth of biomass, C is separated from CO_2 and again $\text{RQ}_{\text{LBM}} = 1$.

2.7. Objectives of Part II

The objectives of Part II are as follows: (i) Present CO_2 (or C) and O_2 balance equations, (ii) obtain solutions for global O_2 production by land and ocean-based biomasses and CO_2 storage by the ocean, (iii) define energy-based $\text{RQ}_{\text{Glob(En)}}$ and estimate it using the curve fit constants for Keeling's curve (linear and quadratic curve fits), (iv) provide explicit formulae for the CO_2 distribution in GT/year and % contribution amongst the atmosphere, land biomass (LBM), and ocean water biomass (OWBM) and the amount stored in ocean water (St, Ocn), (v) validate the results from the RQ method by comparing them with the literature results obtained from more detailed numerical models, which are presented in Global Carbon Project (GCP) reports, and (vi) relate the rate of global temperature rise in terms of $\text{RQ}_{\text{Glob(En)}}$ and annual energy release rate from FFLU.

3. Materials and Methods

3.1. Assumptions

1. Humans and land and ocean-based animals consume renewable energy (not coal, oil, or fossil fuels), which presumes that the CO_2 produced and O_2 consumed by humans and animals is approximately equal to the CO_2 sink and O_2 production in growing "nutrient-crops"; they operate on "closed C" loop.
2. Biomass includes terrestrial (land) and ocean water-based or marine biomass and micro-organisms.
3. CO_2 is released during calcination (cement making without using oxygen), and CO_2 is used in limestone formations in the ocean (without the use of O_2). It can be accounted

for through the definition of an effective RQ_{OWBM} . Note that the C(s) from calcination (cement carbonation) is only 0.2 GT of C/year, while the CO_2 storage in the ocean is 90 GT of C/year.

4. While CO_2 is stored, there is no net O_2 storage in the oceans; there was only a 2% drop in ocean's oxygen levels over the last 50 years [48], and hence, O_2 storage in OW is neglected compared to CO_2 since O_2 in the atmosphere is at much higher concentrations and the ocean is nearly saturated with O_2 due to much higher concentrations of O_2 in the atmosphere compared to CO_2 (note: solubility CO_2 : 0.0116 mL per L per mm Hg, O_2 : 0.00565 mL/L per mm Hg; typically, O_2 saturation level in OW is about 7–8 mg/L, CO_2 0.44–0.66 mg for warm to cold water; O_2 saturation level is high due to the high concentration of O_2 in the atmosphere)).
5. Changes in O_2 and CO_2 storage due to changes in the temperature of ocean water are ignored in CO_2 and O_2 balance equations.

Additional assumptions, if any, are stated as the governing equations are presented.

3.2. CO_2 and O_2 Balance Equations and Solutions for CO_2 Distribution amongst Atmosphere, Land, and Ocean

(i) CO_2 Balance Equations

The C emissions are from fossil fuels via CO_2 (CE_{FF}), and cement production and land use (CE_{LU}), and C sinks are in land biomass (CS_{LBM}) due to the fertilization of plants on land and ocean biomasses (CS_{OWBM}), storage of CO_2 in the atm [44] (CS_{ATM}), and storage in the ocean water ($CS_{St,Ocn}$, i.e., without O_2 production) as dissolved gas and as carbonate.

The C atom balance equation is written as follows:

$$C_{atom} : \{(CE)_{FF} + (CE)_{LU}\} = \{(CS)_{Atm} + (CS)_{LBM} + (CS)_{OWBM} + (CS)_{St,Ocn}\} \quad (4)$$

which can be equally applied to CO_2 since 1 mole of CO_2 contains 1 mole of carbon. Replacing C with CO_2 in Equation (4) and solving for the CO_2 storage rate in the atmosphere yields the following:

$$\left\{ \frac{d[CO_2]}{dt} \right\}_{atm} * 10^{-06} * N_{air} \approx \{ \dot{N}_{CO_2,FFLU} - \dot{N}_{CO_2,LOWBM} - \dot{N}_{CO_2,st,Ocn} \} \quad (5)$$

where $\dot{N}_{CO_2,FFLU} = \dot{N}_{CO_2,FF} + \dot{N}_{CO_2,LU}$, $\dot{N}_{CO_2,LOWBM} = \dot{N}_{CO_2,LBM} + \dot{N}_{CO_2,OWBM}$, $\left\{ \frac{d[CO_2]}{dt} \right\}_{atm}$ is the accumulation rate of CO_2 in the atmosphere, ppm/year, N_{air} is the atmosphere air, in Peta moles, $\dot{N}_{CO_2,FF}$ and $\dot{N}_{CO_2,LU}$ are the annual CO_2 release rates by FFs and LU, $\dot{N}_{CO_2,FFLU}$ is the combined CO_2 from FFs and LU, $\dot{N}_{CO_2,LBM}$ is the CO_2 sink via land biomass, $\dot{N}_{CO_2,OWBM}$ is the CO_2 sink via ocean water-based biomass, $\dot{N}_{CO_2,LOWBM}$ is the combined CO_2 sink via land and ocean water-based biomasses and $\dot{N}_{CO_2,st,Ocn}$ is the CO_2 storage by the oceans, and all rates are in Peta moles/year. Appendix A shows the conversion from ppm of species per year to GT per year.

(ii) O_2 Balance Equation: see Huang et al. [25]:

$$\left\{ \frac{d[O_2]}{dt} \right\}_{atm} * 10^{-6} N_{air} \approx -\dot{N}_{O_2,FFLU} + \dot{N}_{O_2,LOWBM} \quad (6)$$

$$\dot{N}_{O_2,FFLU} = \dot{N}_{O_2,FF} + \dot{N}_{O_2,LU}, \dot{N}_{O_2,LOWBM} = \dot{N}_{O_2,LBM} + \dot{N}_{O_2,OWBM}, \dot{N}_{O_2,FFLU} = \frac{\dot{E}_{FFLU}}{HHVO_2}$$

where $\left\{ \frac{d[O_2]}{dt} \right\}_{atm}$ is the yearly depletion rate of O_2 in the atmosphere, in ppm/year, $\dot{N}_{O_2,FF}$ and $\dot{N}_{O_2,LU}$ are the annual O_2 consumption rates by FFs and LU, $\dot{N}_{O_2,FFLU}$ is the combined O_2 consumed by FFs and LU and is estimated from annual data on energy released by FF and LU, $\{\dot{E}_{FFLU}\}$, $\dot{N}_{O_2,LBM}$ is the O_2 production rate via land biomass, $\dot{N}_{O_2,OWBM}$ is the O_2 production rate via ocean water-based biomass (e.g., PP), $\dot{N}_{O_2,LOWBM}$ is the combined O_2 production rate via land and ocean water biomasses after accounting for the cost of

respiration by plants and microbial decomposition. It is noted that the oxygen consumed by FFLU $\dot{N}_{O_2,FFLU}$ is proportional to energy released by FFLU by various fuel types and as such, % oxygen consumed by each fuel type is the same as % energy released by each fuel type; thus, the energy % (2022) or O_2 % consumed by gas, coal, and oil is 28.7%, 32.7%, and 38.6% [49].

(iii) CO_2 Source/Sink in Atmosphere in terms of RQ

Using the definition of RQ, the CO_2 balance Equation (5) becomes

$$\left\{ \frac{d[CO_2]}{dt} \right\}_{atm} * 10^{-6} * N_{air} \approx \left\{ RQ_{FFLU} \dot{N}_{O_2,FFLU} - RQ_{LOWBM} \dot{N}_{O_2,LOWBM} - \dot{N}_{CO_2,st,Ocn} \right\} \quad (7)$$

$$RQ_{FFLU} \dot{N}_{O_2,FFLU} = RQ_{FF} \dot{N}_{CO_2,FF} + RQ_{LU} \dot{N}_{O_2,LU}, RQ_{LOWBM} \dot{N}_{O_2,LOWBM} = RQ_{LBM} \dot{N}_{O_2,LBM} + RQ_{OWBM} \dot{N}_{O_2,OWBM}$$

Dividing by $\dot{N}_{O_2,FFLU}$, and defining the energy-based $RQ_{Glob(En)}$ as

$$RQ_{Glob(En)} = \frac{\left\{ \frac{d[CO_2]}{dt} \right\}_{atm} (10^{-6} * N_{air})}{\dot{N}_{O_2,FFLU}} = \frac{\left\{ \frac{d[CO_2]}{dt} \right\}_{atm} * F_{Bal}}{\dot{E}_{FFLU}} \quad (8)$$

the dimensionless form of Equation (7) is written as

$$RQ_{Glob(En)} = \left\{ \frac{\left\{ \frac{d[CO_2]}{dt} \right\}_{atm}}{\dot{N}_{O_2,FFLU}} \right\} * N_{air} * 10^{-6} = RQ_{FFLU} - x * RQ_{LOWBM} - y \quad (9)$$

or

$$RQ_{Glob(En)} = \left\{ \frac{\left\{ \frac{d[CO_2]}{dt} \right\}_{atm}}{\dot{E}_{FFLU}} \right\} * F_{Bal} = RQ_{FFLU} - x * RQ_{LOWBM} - y, F_{Bal} = HHV_{O_2} * N_{air} * 10^{-6} = 79.3 \quad (10)$$

where $R_{Glob(en)}$ definition is presented in column 2 and row (6a), of Table 2 and typical values for RQ_{FF} , RQ_{LU} , etc. are presented in Table 3. The definition for F_{Bal} along with their values are presented in Table 4.

$$x = \frac{\dot{N}_{O_2,LOWBM}}{\dot{N}_{O_2,FFLU}} \quad (11)$$

$$y = \frac{\dot{N}_{CO_2,st,ocn}}{\dot{N}_{O_2,FFLU}} = RQ_{FFLU} \frac{\dot{N}_{CO_2,st,ocn}}{\dot{N}_{CO_2,FFLU}} \quad (12)$$

$$RQ_{FFLU} = RQ_{FF} * EF_{FF} + RQ_{LU} * EF_{LU}, EF_{FF} = \frac{\dot{N}_{O_2,FF}}{\dot{N}_{O_2,FFLU}}, EF_{LU} = \frac{\dot{N}_{O_2,LU}}{\dot{N}_{O_2,FFLU}} \quad (13)$$

Further,

$$RQ_{LOWBM} = \frac{\dot{N}_{CO_2,LOWBM}}{\dot{N}_{O_2,LOWBM}} = RQ_{LBM} * (1 - z) + RQ_{OWBM} * z \quad (14)$$

where

$$z = \frac{\dot{N}_{O_2,OWBM}}{\dot{N}_{O_2,LOWBM}}, 1 - z = \frac{\dot{N}_{O_2,LBM}}{\dot{N}_{O_2,LOWBM}} \quad (15)$$

where EF, the Energy fraction contribution by FFs, LU, and z, is a measure of the fraction of oxygen contributed by OWBM to the atm. More discussion on the values of "z" will be given later in Section 4.4.1.

Note that soil absorbs roughly 25% of anthropogenic emissions each year and is stored in peatland or permafrost without a well-defined release of O_2 ; this can be accounted for by altering RQ_{LBM} and RQ_{OWBM} ; see Refs. [27,28].

3.3. Solutions for O₂ Production, CO₂ Storage in Ocean, and Carbon Budget Solutions for O₂ Production and CO₂ Storage in Ocean

The CO₂ and O₂ balance equations indicate that the atmospheric O₂ and CO₂ in the Keeling curve are affected by O₂ consumption and CO₂ production via FFLU, O₂ production, and CO₂ sink by land and ocean biomasses and ocean storage. Thus, the two equations (Equations (6) and (7)) can be solved for two unknowns: O₂ production by biomass, $\dot{N}_{O_2,LOWBM}$, and CO₂ storage by ocean, $\dot{N}_{CO_2,st,Ocn}$. Appendix B presents the normalization of Equations (9) and (10) and describes the solution procedure. The solutions for the non-dimensional form of O₂ production rate (x) and CO₂ storage rate (y) are obtained and presented in Rows 7 and 10 of Table 2. It also lists a summary of all the solutions. Note that “y” is not RQ even though both are ratios of CO₂ to O₂.

Rows 1 and 2: Curve Fit Constants for CO₂ and O₂.

Rows 3a and 3b: Slopes of CO₂ in ppm/year and GT/year.

Rows 4a and 4b: Slopes of O₂ in ppm/year and GT/year.

Rows 7 and 10: Solutions for “x” and “y”.

The net O₂ moles transferred by ocean and land biomasses to the atmosphere per unit of O₂ consumed by FFLU are given as

$$\frac{\dot{N}_{O_2,OWBM}}{\dot{N}_{O_2,FFLU}} = z * x \quad (16)$$

$$\frac{\dot{N}_{O_2,LBM}}{\dot{N}_{O_2,FFLU}} = (1 - z) * x, \quad (17)$$

See Rows 8 and 9 in Table 2 for the O₂ contribution by ocean and land biomasses.

3.4. Global RQ_{Glob} and Energy-Based RQ_{Glob(En)}

Global RQ: Part I [9] defined RQ_{Glob} as follows (Column 2, Row 5 of Table 2):

$$RQ_{Glob} = \frac{\left\{ \frac{d[CO_2]}{dt} \right\}_{atm}}{\left| \frac{d[O_2]}{dt} \right|_{atm}} \quad (18)$$

where d[CO₂]/dt is the addition rate of CO₂ to the atmosphere. Both CO₂ and O₂ slopes are known from Keeling’s data and in terms of curve fit constants.

Energy-based RQ_{Glob(En)}: Definition is given in Equations (8) and (10). If energy data are not available for the year of interest (i.e., 2006) and instead, C data are available in GT/year, then C in Peta Moles per year = {C(s) in GT per year/12.01}, which is the same as CO₂ in Peta Moles/year. Then the required O₂ in Peta moles is given as {CO₂ in Peta moles per year / RQ_{FFLU}}.

Table 2. List of formulae for estimation of global respiratory quotient of planet, CO₂ distribution amongst the atmosphere, land biomass (LBM), ocean water biomass (OWBM), and ocean water storage (St, On). For list of “F” values in many relations, see Table 4. For data on constants a₀, a₁... j₀, j₁, see Section 3.4.2. Unless otherwise stated, most of the results on CO₂ budget are energy-based. For the year 2006, the quantitative numbers generated by the current method are in curly brackets { }, while the reported data are in square brackets []. Unless otherwise stated, the GT per year denotes GT of CO₂ per year.

#	Variable	Linear Fit Numbers for 2006 in Parenthesis { }	Quadratic Fit (Also Called Parabolic Fit) Numbers for 2006 in Parenthesis { }
Curve Fit Constants and Slopes of Keeling’s curves on CO ₂ and O ₂			
1	Linear Fit of Keeling’s curve: CO ₂ in atmosphere, ppm	a ₁ * years + a ₀ , linear fit {Est. CO ₂ for year 2006 = 381.7 ppm} [Keeling’s data 382.1 ppm]	c ₂ * years ² + c ₁ * years + c ₀ , {CO ₂ for year 2006 = 380.5 ppm} [Keeling’s data 382.1 ppm]
2	O ₂ in atmosphere ppm	b ₁ * years + b ₀ {Est O ₂ for year 2006 = 209421.4 ppm} [Keeling’s data: 209,423 ppm]	d ₂ * years ² + d ₁ * years + d ₀ , d ₂ = −0.0435 ppm/year ² , d ₁ = −3.0332 ppm/year, {Est O ₂ for year 2006 = 209,424.6 ppm} [Keeling’s data: 209,423]
3a	d[CO ₂]/d(year) = CO ₂ change per year, ppm in atmosphere /year	a ₁ {2.081 ppm/year, constant, independent of year}	2 * c ₂ * years + c ₁ {2.04 ppm/year in 2006}
3b	d (CO ₂)/d(year), GT/year 1 ppm of CO ₂ in atmosphere = 7.79 GT	7.79 * a ₁ {16.2 in 2006, independent of year} [13.7 in 2006, 7% imbalance]	7.79 * 2 * c ₂ * years + c ₁ {15.9 in 2006} [13.7 in 2006, 7% imbalance]
4a	d[O ₂]/d(year), ppm/year 1 ppm of O ₂ in atmosphere = 5.66 GT	b ₁ , negative {−4.44 ppm/year, constant, independent of year}	2 * d ₂ * years + d ₁ {−4.34 ppm/year in 2006}
4b	d(O ₂)/d(year)dO ₂ /dt, GT removed from atmosphere/year	5.66 b ₁ , b ₁ in ppm/year {25.12 GT/year, constant and independent of year}	{(15.58 * d ₂ * year + 7.79 * d ₁) {24.59 GT/year in 2006}
Global RQ			
5	$RQ_{Glob} = \frac{\left(\frac{d[CO_2]}{dt}\right)_{atm}}{\left(\frac{d[O_2]}{dt}\right)_{atm}}$	$\frac{a_1}{ b_1 }$, constant {0.468 constant, independent of year}	$\left(\frac{2*c_2*year+c_1}{2*d_2*year+d_1}\right)$, decreases slightly with years, {0.470 in 2006}

Table 2. Cont.

#	Variable	Linear Fit Numbers for 2006 in Parenthesis { }	Quadratic Fit (Also Called Parabolic Fit) Numbers for 2006 in Parenthesis { }
Curve Fit Constants and Slopes of Keeling's curves on CO ₂ and O ₂			
6a	$RQ_{Glob}(En) = \frac{\left(\frac{d[CO_2]}{dt}\right)_{atm} * (10^{-6} * N_{air})}{\dot{N}_{O_2,FFLU}}$ With Energy data, {d[CO ₂]/dt}, ppm/year	$\frac{F_{Bal} * a_1}{\dot{E}_{FFLU}} = RQ_{Glob}, * \left\{ \frac{F_{Bal} * b_1}{\dot{E}_{FFLU}} \right\},$ $\dot{E}_{FFLU} \text{ in Exa J/Year, } a_1, b_1, \text{ ppm/year, } F_{Bal} = 79.3 \text{ (see Table 4 for } F_{Bal} \text{ relation)}$ {0.358 in 2006}	$\frac{F_{Bal} * (2 * c_2 * year + c_1)}{\dot{E}_{FFLU}},$ $RQ_{Glob}, * \left\{ \frac{F_{Bal} * (2 * d_2 * years + d_1) }{\dot{E}_{FFLU}} \right\}$ $\dot{E}_{FFLU} \text{ in Exa J/Year, } a_1, b_1, \text{ ppm/year}$ {0.352 in 2006}
6b	$RQ_{Glob}(En) = \frac{\left(\frac{d[CO_2]}{dt}\right)_{atm} * (10^{-6} * N_{air})}{\dot{N}_{O_2,FFLU}}$ With C data in GT/year, {d[CO ₂]/dt}, ppm/year	$\frac{F_{CGt} * a_1}{(\dot{C}_{FFLU} / RQ_{FFLU})} = RQ_{Glob}, * \left\{ \frac{F_{CGt} * b_1}{\dot{E}_{FFLU}} \right\}$ (see Table 4 for F _{CGt} relation) $F_{CGt} = 2.13, \text{ in GT/Year, } a_1, b_1, \text{ ppm/year,}$ {0.36 in 2006}	$\frac{F_{CGt} * (2 * c_2 * year + c_1) * RQ_{FFLU}}{\dot{C}_{FFLU}},$ $RQ_{Glob}, * \left\{ \frac{F_{CGt} * (2 * d_2 * years + d_1) * RQ_{FFLU}}{\dot{C}_{FFLU}} \right\}$ $\dot{C}_{FFLU} \text{ in GT/Year, } a_1, b_1, \text{ ppm/year,}$ {0.36 in 2006}
6c	$RQ_{Glob}(En) = \frac{\left(\frac{d[CO_2]}{dt}\right)_{atm} * (10^{-6} * N_{air})}{\{d[CO_2]/dt\}, \text{ ppm/year}}$	$\left(\frac{d[CO_2]}{dt}\right)_{atm}, F_{CO_2} = 0.0126$ $F_{CO_2} \dot{E}_{FFLU}$	$\frac{\left(\frac{d[CO_2]}{dt}\right)_{atm}}{F_{CO_2} \dot{E}_{FFLU}}$ $F_{CO_2} = 0.0126$
Non-Dimensional Solutions for O ₂ Production and CO ₂ Storage in Ocean			
7a	$x = \frac{\dot{N}_{O_2,LOWBM}}{\dot{N}_{O_2,FFLU}},$	$\left\{ 1 - \frac{F_{Bal} * b_1 }{\dot{E}_{FFLU}} \right\}, F_{Bal} = 79.3$ {0.24 in year 2006 with FFLU Energy/year =460.1 Exa J/year}	$\left\{ 1 - \frac{F_{Bal} * (2 * d_2 * years + d_1) }{\dot{E}_{FFLU}} \right\}$ {0.25 in year 2006}
7b	$x = \frac{\dot{N}_{O_2,LOWBM}}{\dot{N}_{O_2,FFLU}}$ With C data	$x = 1 - \left\{ \frac{F_{CGt} * b_1 * RQ_{FFLU}}{\dot{C}_{FFLU}} \right\}, F_{CGt} = 2.13$ $\dot{C}_{FFLU}, \text{ carbon output GT/year by FFLU}$ {0.24 with C data of 9.71 GT/year in 2006}	$x = 1 - \left\{ \frac{F_{CGt} * (2 * d_2 * years + d_1) * RQ_{FFLU}}{\dot{C}_{FFLU}} \right\}, F_{CGt} = 2.13$ {0.26 in 2006}
7c	Total O ₂ prod GT/year, LOWBM Combined Ocean and land biomasses	$F_{O_2BM} * x * \dot{E}_{FFLU}$ $F_{O_2BM} = 0.0714$ {7.72 GT/year in 2006 with x = 0.235}	$F_{O_2BM} * x * \dot{E}_{FFLU}, F_{O_2BM} = 0.0714$ {8.25 GT/year in 2006 with x = 0.2516}
8	Ocean BM Contrib. O ₂ $\frac{\dot{N}_{O_2,OWBM}}{\dot{N}_{O_2,FFLU}}$	$z * x, \text{ where } x \text{ for linear fit}$ {0.024 in 2006 with z = 0.1}	$z * x, \text{ where } x \text{ for quadratic fit}$ {0.025 in 2006 with z = 0.1}

Table 2. Cont.

#	Variable	Linear Fit Numbers for 2006 in Parenthesis { }	Quadratic Fit (Also Called Parabolic Fit) Numbers for 2006 in Parenthesis { }
Non-Dimensional Solutions for O ₂ Production and CO ₂ Storage in Ocean			
9	Land BM Contrib. O ₂ $\frac{\dot{N}_{O_2,LBM}}{\dot{N}_{O_2,FFLU}}$	$(1 - z) * x$ {0.21 in 2006 with z = 0.1}	$(1 - z) * x$, where x for quadratic fit {0.23 in 2006 with z = 0.1}
10	CO ₂ storage $y = \frac{\dot{N}_{CO_2,St,Ocn}}{\dot{N}_{CO_2,FFLU}}$	$y = RQ_{FFLU} - RQ_{LOWBM} * x - RQ_{Glob(En)}$ Or $RQ_{FFLU} - RQ_{LOWBM} + \frac{[b_1 * F_{Bal} * \{RQ_{LOWBM} - RQ_{Glob}\}]}{\dot{E}_{FFLU}}$ {0.187}	$y = RQ_{FFLU} - RQ_{LOWBM} * x - RQ_{Glob(En)}$ Or $\frac{RQ_{FFLU} - RQ_{LOWBM} + [(2*d_2*years+d_1)]*F_{Bal}*\{RQ_{LOWBM}-RQ_{Glob}\}}{\dot{E}_{FFLU}}$ {0.178}
CO ₂ Budget Amongst Atmosphere, Land, and Ocean			
11	$CO2_{Fr,atm} = \frac{\dot{N}_{CO_2,atm}}{\dot{N}_{CO_2,FFLU}}$	$\frac{a_1 * F_{Bal}}{\dot{E}_{FFLU} * RQ_{FFLU}}$ or $\frac{RQ_{Glob(En)}}{RQ_{FFLU}}$ {0.46 in 2006}	$\frac{F_{Bal} * (2 * c_2 * year + c_1)}{\dot{E}_{FFLU} * RQ_{FFLU}}$ {0.45 in 2006}
12	$CO2_{Fr,LOWBM} = \frac{\dot{N}_{CO_2,LOWBM}}{\dot{N}_{CO_2,FFLU}}$	$\frac{RQ_{LOWBM} * x}{RQ_{FFLU}}$ {0.30 in 2006}	$\frac{RQ_{LOWBM} * x}{RQ_{FFLU}}$ {0.32 in 2006}
13	$CO2_{Fr,St,Ocn} = \frac{\dot{N}_{CO_2,St,Ocn}}{\dot{N}_{CO_2,FFLU}}$	$1 - x \frac{RQ_{LOWBM}}{RQ_{FFLU}} - \left\{ \frac{F_{Bal} * a_1}{RQ_{FFLU} * \dot{E}_{FFLU}} \right\} * \frac{y}{RQ_{FFLU}}$ {0.24 in 2006 with Energy data}	$1 - x \frac{RQ_{LOWBM}}{RQ_{FFLU}} - \left\{ \frac{F_{Bal} * (2 * c_2 * years + c_1)}{RQ_{FFLU} * \dot{E}_{FFLU}} \right\}$ {0.23 in 2006 with Energy data}
14	CO ₂ sink Fr via Ocean Biomass $\frac{\dot{N}_{CO_2,OWBM}}{\dot{N}_{CO_2,FFLU}}$	$\left(\frac{RQ_{OWBM}}{RQ_{FFLU}} \right) * z * x$, {0.030 in 2006}	$\left(\frac{RQ_{OWBM}}{RQ_{FFLU}} \right) z * x$ {0.032 in 2006 with z = -0.1}
15	CO ₂ sink Fr Ocean Total $\frac{\dot{N}_{CO_2,St,Ocn} + \dot{N}_{CO_2,OWBM}}{\dot{N}_{CO_2,FFLU}}$	$\frac{y}{RQ_{FFLU}} + \left(\frac{RQ_{OWBM}}{RQ_{FFLU}} \right) * z * x$ or $1 - \frac{RQ_{Glob(En)}}{RQ_{FFLU}}$ {0.27 in 2006 with z = 0.1} {0.25 in 2006}	$\frac{y}{RQ_{FFLU}} + \left(\frac{RQ_{OWBM}}{RQ_{FFLU}} \right) * z * x$ {0.26 in 2006 with z = -0.1} {0.25 in 2006}
16	CO ₂ sink Fr LBM $\frac{\dot{N}_{CO_2,LBM}}{\dot{N}_{CO_2,FFLU}}$	$\left(\frac{RQ_{LBM}}{RQ_{FFLU}} \right) (1 - z) * x$ {0.27 in 2006 with z = 0.1} {0.33 in 2006 from data}	$\left(\frac{RQ_{LBM}}{RQ_{FFLU}} \right) * (1 - z) * x$ {0.29 in 2006 with z = 0.1} {0.33 in 2006 from data}

Table 2. Cont.

#	Variable	Linear Fit Numbers for 2006 in Parenthesis { }	Quadratic Fit (Also Called Parabolic Fit) Numbers for 2006 in Parenthesis { }
CO ₂ Budget Amongst Atmosphere, Land, and Ocean			
17	CO ₂ sink by land and ocean biomasses, GT/year	$RQ_{LOWBM} * M_{CO_2} * \left\{ \frac{\dot{E}_{FFLU}}{HHV_{O_2}} - F_{ppm} * b_1 \right\}$ {10.5 GT/year in 2006}	$RQ_{LOWBM} * M_{CO_2} * \left\{ \frac{\dot{E}_{FFLU}}{HHV_{O_2}} - F_{ppm} * (2 * d_2 * year + d_1) \right\}$ {11.2 GT/year in 2006}
18	CO ₂ sink by ocean biomass, GT/year	$z * \text{CO}_2 \text{ sink by land and ocean biomasses in GT/year}$ {1.05 GT/year in 2006 with $z = -0.1$ } No previous data to compare	$z * \text{CO}_2 \text{ sink by land and ocean biomasses in GT/year}$ {1.12 GT/year in 2006 with $z = -0.1$ } No previous data to compare
19	CO ₂ sink by land biomass, GT/year	$(1 - z) * \text{CO}_2 \text{ sink by land and ocean biomasses in GT/year}$ {9.45 GT/year in 2006 with $z = -0.1$ } {11.06 GT/year in 2006} [28]	$(1 - z) * \text{CO}_2 \text{ sink by land and ocean biomasses in GT/year}$ {10.08 GT/year in 2006 with $z = -0.1$ } {11.06 GT/year in 2006} [28]
20	CO ₂ storage by ocean, GT/year	$F_{CO_2EJ} * y * \dot{E}_{FFLU}, F_{CO_2EJ} = M_{CO_2}/HHV_{O_2} = 0.1$ {8.63 GT/year in 2006} {8.36 GT/year in 2006} [50]	$F_{CO_2EJ} * y * \dot{E}_{FFLU}, F_{CO_2EJ} = M_{CO_2}/HHV_{O_2} = 0.1$ {8.21 GT/year} {8.36 (GT/year in 2006)} [50]
Global Temperature and Earth's Mass Loss			
21a	Global Temperature, °C vs. year	$g_1 * (\text{year} - 1991) + g_0$	-
21b	Global Temperature rise ΔT , °C vs. CO ₂ of atmosphere in ppm.	$h_1 \left(\frac{[CO_2]}{[CO_2]_{0,atm}} \right) + h_0$, [CO ₂] _{0,atm} = 355 ppm in 1991 {2006, T in °C = 12.17; Data 12.06 °C}	$\Delta T, °C = h_1 \left(\frac{[CO_2]}{[CO_2]_{0,atm}} \right) + h_0$, $h_1 = 4.0, h_0 = -4.10, [CO_2]_{0,atm} = 354 \text{ ppm}$,
22a	Rate of Temperature rise per year, dT/d(year) in terms of Keeling's data $\frac{dT}{dt} = \frac{h_1}{[CO_2]_{0,atm}} \left(\frac{d[CO_2]}{dt} \right)_{atm}$ {d[CO ₂]/dt}, ppm/year, [CO _{2,0}], ppm	$\frac{h_1 a_1}{[CO_2]_{0,atm}}, h_1 = 4.0$ $4 * (a_1/a_0)$ {1995 to 2022}, dT/year = 0.024 °C /year	$\frac{h_1 (2 * c_2 * years + c_1)}{[CO_2]_{0,atm}}$ Years = Year of interest—1991 {1995 to 2022, dT/year = 0.023 °C/year }
22b	Rate of Temperature rise per year, dT/d (year) Energy data	$F_{dTdt} * RQ_{Glob(En)} * \dot{E}_{FFLU}, F_{dTdt} = 1.44 \times 10^{-4}$	$F_{dTdt} * RQ_{Glob(En)} * \dot{E}_{FFLU}, F_{dTdt} = 1.44 \times 10^{-4}$
23	Earth's mass Loss Rate, GT/year	$F_{CGTE} * RQ_{Glob(En)} * \dot{E}_{FFLU}$, Alternate: $F_{CGT} * (d[CO_2]/dt)_{qtm}$ {4.42 GT/year, 2006}	$F_{CGTE} * RQ_{Glob(En)} * \dot{E}_{FFLU}$, Alternate: $F_{CGT} * (d[CO_2]/dt)_{qtm}$ {4.34 GT/year, 2006}

Table 3. RQ values selected for quantitative results.

Source or Sink of Interest	RQ
Fossil Fuels, FFs	0.75
Land Use, LU	1.0
Combined FFs and LU	$EF_{FF} * RQ_{FF} + EF_{LU} * RQ_{LU} = 0.778$
Land Biomass, LBM	1.0
Ocean water-based biomass, OWBM	0.87
Com Combined LBM + OWBM;	$(1 - z) * RQ_{LBM} + (1 - z) * RQ_{OWBM} = 0.987$ With $z = 0.1$

Table 4. The constants F: Relations and values. The subscripts for F indicate the “relations” where they were used, e.g., F_{dTdt} represents constants in the relation for dT/dt , etc.

Constants F	Relation	Value
F_{Bal} (item 6a, Table 2)	$10^{-6} * N_{air} * HHV_{O2}$	79.3
F_{CGT} (item 6b, Table 2)	$F_{CGT} = 10^{-6} * N_{air} * M_C$	2.13
F_{CEJ} (item 7c, Table 2)	(M_C / HHV_{O2})	0.0268
F_{CO2}	$\left(\frac{10^6}{N_{air} * HHV_{O2}} \right) = \frac{1}{F_{Bal}}$	0.0126
F_{CO2EJ} (item 20, Table 2)	$\frac{M_{CO2}}{HHV_{O2}}$	0.1
F_{O2BM} (item 7c, Table 2)	$\frac{M_{O2}}{HHV_{O2}}$	0.0714
F_{ppm} (item 17, Table 2)	$10^{-6} * N_{air}$	0.177
F_{dTdt} (Equation (36))	$\left\{ \frac{h_1 * F_{CO2}}{[CO_{2,0}]} \right\}$	$1.44 \times 10^{-4}, h_1 = 4$

3.4.1. CO₂ Budget amongst Atmosphere, Land, and Ocean Biomasses and Ocean Storage

The solutions for CO₂ stored in the atmosphere, CO₂ sink by biomass, and CO₂ storage are presented in Appendix B. Appendix B provides the details of derivations.

Rows 11, 12, and 13: CO₂ stored in the atmosphere, CO₂ sink by biomass, and CO₂ storage in the ocean.

Rows 14 and 16: CO₂ stored in land biomass and ocean biomass.

Row 15: Combined CO₂ storage in the ocean and ocean biomass CO₂ stored in land biomass, ocean biomass.

Row 16: CO₂ fraction by land biomass.

Row 4b, and Rows 17–20 in GT/year for CO₂ sink in the atmosphere, combines land and ocean biomasses, ocean biomass, land biomass, and CO₂ stored in the ocean.

3.4.2. Data Used in Calculations

Input Data:

Curve fit constants.

Linear Fit [9]: $d[CO_2]/dt = a_1 * years + a_0$, $d[O_2]/dt = b_1 * years + b_0$, years = current year – 1991, linear fit $a_0 = 350.5$ ppm, $a_1 = 2.081$ ppm/year, $R^2 = 0.97$, and O₂ data, $b_0 = 209488$ ppm, $b_1 = -4.438$ ppm/year $R^2 = 0.98$.

Quadratic Fit [9]: $d[CO_2]/dt = c_2 * years^2 + c_1 * years + c_0$, $d[O_2]/dt = d_2 * years^2 + d_1 * years + d_0$, $c_2 = 0.01892$, $c_1 = 1.473$, $c_0 = 354.1$, $R^2 = 0.98$: O₂ data, $d_0 = 209,480$ ppm, $d_1 = -3.0332$ ppm/year, $d_2 = -0.0435$ ppm/year², $R^2 = 0.99$.

Global Average Temp vs. year, See Equation (31) and Row 21a of Table 2, $g_0 = 13.7$, $g_1 = -5.281 * 10^{-3}$, $g_2 = 9.114 * 10^{-5}$, $R^2 = 0.90$, years from 1880 to 2023.

Global Temp. See Equation (33) and Row 21b of Table 2, $\Delta T = T - T_{0,91}$ vs. $[CO_2]/[CO_{2,0}]$, $h_1 = 4.0$, $h_0 = -4.10$, $R^2 = 0.86$, $[CO_{2,0}] = 355$ ppm with 1991 data.

Global $\frac{\dot{E}_{FFLU}}{\dot{E}_{FFLU,0}}$ vs. $\frac{[CO_2]}{[CO_2]_0}$, See Equation (37) $i_1 = 4.14$, $i_0 = -3.16$, $R^2 = 0.98$.

Global $\frac{[CO_2]}{[CO_2]_0}$ vs. $\frac{\dot{E}_{FFLU}}{\dot{E}_{FFLU,0}}$. See Equation (37), $j_1 = 0.24$, $j_0 = 0.76$, $R^2 = 0.98$.

RQ's: $RQ_{OWBM} = 0.84$, which is close to 0.86, suggested in [51].

$RQ_{FFLU} = 0.78$; compare with values in Ref. [52]: $PQ = 1.1$ or $RQ_{LBM} = 0.91$ for terrestrial plants [9].

O₂ Moles Consumed from FFLU Energy: $\{ \dot{N}_{O_2,FFLU} \}$ from energy data = $\frac{\dot{E}_{FFLU}}{HHV_{O_2}}$

Atmosphere Properties:

Nair = 1.77×10^5 Peta mol, Oxygen Concentration: 0.21 or 210,000 ppm.

One ppm of CO added to the atmosphere = 0.177 Peta moles of CO₂ added, 7.79 GT of CO₂ added to the atmosphere, or 2.12 GT of Carbon added to the atmosphere.

One ppm of O₂ removed from the atmosphere, 1 ppm = 0.177 Peta moles removed, or 5.66 GT of O₂ removed from the atmosphere.

C Imbalance % in literature data: $100 * \{CO_2 \text{ source from FFLU} - CO_2 \text{ sink in (atmosphere + land + ocean)}\} / FFLU \text{ CO}_2$

Adjustable parameter "z" (O₂ transferred from ocean to atmosphere/Total O₂ produced by LBM and OWBM).

2006 Data

$\{ \dot{E}_{FFLU} \} = 408.25$ (FF) + 51.96 (LU) = 460.21 Exa J; $\dot{C}_{FFLU} = 9.71$ GT/year

LU energy = 11.3% of total energy from LU or 12.7% of FF energy

C (from FFLU) data in 2006: 9.71 GT/year or CO₂ data: 35.6 GT of CO₂ /year

$\{ \dot{N}_{O_2,FFLU} \} = 1.027$ Peta moles /year.

3.4.3. Literature Results on CO₂ in Atmosphere, Land, and Ocean

Fossil and LU based CO₂ and energy data are from Ref. [50]. Atmosphere CO₂ data are from [53]. Ocean sink data are estimated from the average of several global ocean biogeochemistry models [44] and the ocean sink uncertainty of ± 0.5 GT C/year. Land sink data are from the average of dynamic global vegetation models and uncertainty of ± 0.9 GT C/year.

The C or CO₂ budget in literature is based on several "stand-alone" land and detailed ocean circulation models. The Global Carbon Budget (GCB) is published by the Global Carbon Project; a summary of various models is provided in [44]. The land sink for C is based on the average of global vegetation models [54]. The estimates on ocean storage are based on global ocean-atmosphere CO₂ flux using ocean surface CO₂ concentration gradients, satellite data, and an average of several global ocean biochemistry models.

4. Results and Discussion

Table 2 contains all necessary formulae for all the important results required in obtaining CO₂ distribution amongst the atmosphere, land, and ocean. The Supplemental Materials titled "Supp Step by Step CO₂ budget" describe the step-by-step procedure for obtaining the quantitative results for the year 2006 shown in Table 2 and most of the results presented in Sections 4.1–4.5. An Excel-based program was developed with input data from Section 3.4.2 and an output containing all the results for the variables is listed in Table 2. For 2006, computed numbers generated by the current method are shown in curly brackets {}, while the previous literature data obtained with more detailed models are presented within square brackets [] as the last line of each row in the third and fourth columns of Table 2.

(i) The results for the global respiratory quotients (RQ_{Glob} , $RQ_{Glob(En)}$), normalized O₂ production ("x") and CO₂ storage ("y"), and energy released by FFLU vs. year will be presented first. (ii) The year 2006 was then selected for parametric studies since it was somewhere within the median year for data reported in 1991–2020 (30-year period), for which period the curve fits on Keeling's data were obtained. (iii) The CO₂ in GT/year and % contributed by the atmosphere, land, and ocean storage will be compared with

previous data for 2006 with z as a parameter, and a suitable z value will be selected. For the year 2006, FFLU energy is reported as 460.2 Exa J and CO₂ emission is reported as 35.6 GT of CO₂ by FFLU. The RQ_{FFLU} is estimated at 0.78 (Part I) [9]. Typically, the more oxygen in FFs, the lesser the stoichiometric oxygen, the higher the RQ, and the higher the CO₂ emission per Exa J (Equation (3)). (iv) Then, using the selected z value, the annual RQ-based results on CO₂ distribution in the atmosphere, land, and ocean storage in GT/year and % vs. year for the years 1991 to 2018 will be compared with the previous data. (v) Based on current analysis, various methods of freezing CO₂ growth in atmosphere will be presented followed by presentation of relations between global temperature, rate of heating, Energy, and global CO₂ Concentration.

4.1. Global Respiratory Quotients (RQ_{Glob} , $RQ_{\text{Glob(En)}}$)

Part I dealt with RQ_{Glob} , estimated as 0.47 using Keeling's data (Row 5, Table 2) and remaining constant with linear fit. RQ_{Glob} decreases from 0.48 to 0.46 (1991–2020) for quadratic fit [part I, [9]] and $RQ_{\text{Glob}} = 0.47$ in 2006. It appears that Earth behaves like a large "Hypothetical Biological System (HBS)" (or "barren Earth" without chlorophyll and oceans) to sustain the lifelong activities of humans on Earth with the net effect of increasing CO₂ at the cost of decreasing O₂ in the atmosphere. For a linear fit on CO₂ data, the rate of increase in CO₂ is constant at 2.08 ppm/year, and the intercept on the Y-axis, i.e., CO₂ concentration in ppm in 1991, is 355 ppm; but for quadratic curve fits, the intercept is 354 ppm (CO₂ concentration in 1991), $d(\text{CO}_2/\text{dt})$ starts at 1.47 ppm/year in 1991, and increases to 2.04 ppm/year in 2006, and 2.57 ppm/year in 2020, indicating the faster growth rate of CO₂ concentration in the atmosphere. According to data posted by the Mauna Loa Observatory (MLO), $d(\text{CO}_2)/\text{dt} = 2.04$ ppm/year and 2.43 ppm/year for 2001–2010 and 2011–2020, respectively [55]. Later, it was shown that the rate of global average temperature is closely coupled to the rate of increase in CO₂ concentration in the atmosphere [Section 4.6].

Figure 2 depicts a large hypothetical biological system (HBS) and the caption has a brief explanation of the figure. This HBS within the dashed boundary includes the land and ocean, while the atmosphere is outside the dashed boundary. The Earth's RQ_{Glob} of 0.47 indicates the release of 0.47 moles of CO₂ into the atmosphere (which is outside the dashed boundary) for every 1 mol of O₂ depleted from the atmosphere. How does Earth's RQ_{Glob} compare with the RQ of humans? Consider a normal human (NH) born with a mass of 3 kg and grown to a mass of 70 kg with the intake of food, broken down into three components: Carbohydrates (CH), Fats (F), and Protein (P). The oxygen moles breathed in from the atmosphere are used for the oxidation of CH and F for the energy needs of the warm human body and the production of CO₂, which is breathed out into the atmosphere. The "P" increases the body mass to almost 70 kg during the period of life. The RQ of NH is about 0.8, indicating that 0.8 moles of CO₂ are breathed out into the atmosphere for every mol of O₂ used for oxidation. The "fuel" or "nutrient" oxidized is a mix of CH and F, 67% CH and 33% F on a mole basis (or 58% of CH and 42% of F on a mass basis) oxidized to CO₂ and H₂O at an RQ of NH = 0.8 [56]. The liver stores excess "fuel" as glycogen for delivery between meals. Note that the mass of humans increases during food intake and decreases between the meals due to the transfer of glycogen through the bloodstream and subsequent oxidation to CO₂ and H₂O. But the average weight of NH increases from birth to death.

Now consider a hypothetical human (HH) (or HBS), born with a large mass of 5.97×10^{12} GT, which includes a mass of FFs stored within the body along with non-combustible matter, and AI-created "chlorophyll" skin. A part of FFs is stored, (unmined FF) and the remaining part (mined FF) is oxidized to CO₂ and H₂O annually for energy release to satisfy the energy needs of the HH. As opposed to NH, the HH produces O₂ from CO₂ using solar energy entering through the skin, which uses a part of the CO₂ produced via the oxidation of FFs into C(s), which adds mass to the HH. Thus, O₂ for oxidation comes from both the O₂ produced and O₂ "breathed" in from the atmosphere. Further, the blood of the

HH (equivalent to oceans of Earth) has the capability of storing a part of CO_2 and, hence, breathing out the remaining CO_2 into the atmosphere. The RQ_{Glob} of this HH or HBS is 0.47, indicating net CO_2 moles of 0.47 (or 0.47 moles of C or 5.84 kg of C) released into the atmosphere for every 1 mol of O_2 breathed in from the atmosphere (Figure 2). Unlike an NH with increasing weight during the life cycle, the HH or HBS loses mass during its life cycle. The NH maintains a constant internal temperature (37°C , called homeostasis), while the HH or HBS is constantly under “fever.”

Figure 2 depicts a thermodynamic description of the HBS of Earth’s mass, which includes the ocean and land (system within the dashed boundary) surrounded by the atmosphere. For planet Earth, the C loss via breathing out is the mass difference between the C mined as FF from the planet and the sum of C deposited for the growth of biomass on land and C(s) stored in the oceans (which adds weight to the land and oceans).

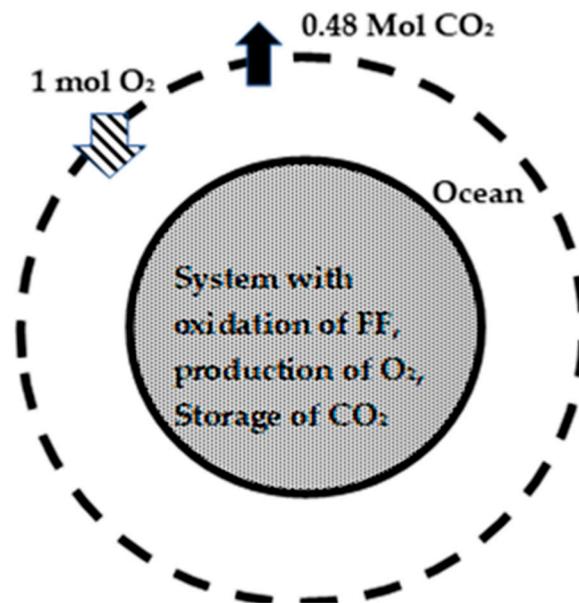


Figure 2. Hypothetical BS (HBS), within dashed boundary. The HBS includes land (shaded) and ocean (white space between solid and dashed circle). The HBS depletes (or “breathes in”) 1 mole of O_2 from atmosphere located outside the dashed boundary and releases 0.47 moles CO_2 (or “breathes out” 0.47 moles of CO_2) into the atm.

While RQ_{Glob} has a better physical meaning, the $RQ_{\text{Glob(En)}}$ is convenient for obtaining results for the CO_2 budget in terms of energy release from FFLU. Figure 3 shows the variations in (i) RQ_{Glob} (primary axis), (ii) $RQ_{\text{Glob(En)}}$ (primary axis), (iii) energy released by FFLU in Exa J/year (secondary axis), and (iv) normalized O_2 production (“x”, primary axis) and CO_2 storage (“y”, primary axis) for the years 1991–2020. The RQ_{Glob} slightly decreases, revealing the increasing ocean acidity as discussed in Part I [9], but the $RQ_{\text{Glob(En)}}$ remains almost flat, indicating that the CO_2 moles added to the atmosphere per Exa J energy released from FFLU energy remain constant, i.e., almost constant RQ_{FFLU} or constant FF mix. Also, $RQ_{\text{Glob(En)}} < RQ_{\text{Glob}}$ since the denominator of $RQ_{\text{Glob(En)}}$ depends on O_2 consumption by FFLU $\{\dot{N}_{\text{O}_2, \text{FFLU}}\}$, which is a sum of O_2 transfer from the atmosphere to power systems $\{\dot{N}_{\text{O}_2, \text{atm}}\}$ and O_2 production by LOWBM, $\{\dot{N}_{\text{O}_2}\}_{\text{LOWBM}}$ while the denominator of RQ_{Glob} is $\{\dot{N}_{\text{O}_2, \text{atm}}\}$.

Recall from Part I that the RQ_{Glob} represents the ratio of two slopes of Keeling data on CO_2 and O_2 and, hence, requires both CO_2 and O_2 data in the atmosphere. However, $RQ_{\text{Glob(En)}}$ requires a knowledge of CO_2 data in the atmosphere and annual energy consumption. It also enables the following relations for estimating the CO_2 mass added to the atmosphere per unit energy release from FFLU.

$$CO_2, \left(\frac{GT}{ExaJ} \right) = F_{CO_2EJ} RQ_{Glob(En)}, F_{CO_2EJ} = \frac{M_{CO_2}}{HHV_{O_2}} = 0.1 \quad (19)$$

$$C \left(\frac{GT}{ExaJ} \right) = \left\{ \frac{M_C}{HHV_{O_2}} \right\} RQ_{Glob(En)} = F_{CEJ} * RQ_{Glob(En)}, F_{CEJ} = \left\{ \frac{M_C}{HHV_{O_2}} \right\} = 0.027 \quad (20)$$

For the year 2006, $RQ_{Glob(En)} = 0.36$ with reported energy data and with reported C data and CO_2 in $GT/Exa J \approx 0.036$ (Equation (19)). Both estimations are very close to each other.

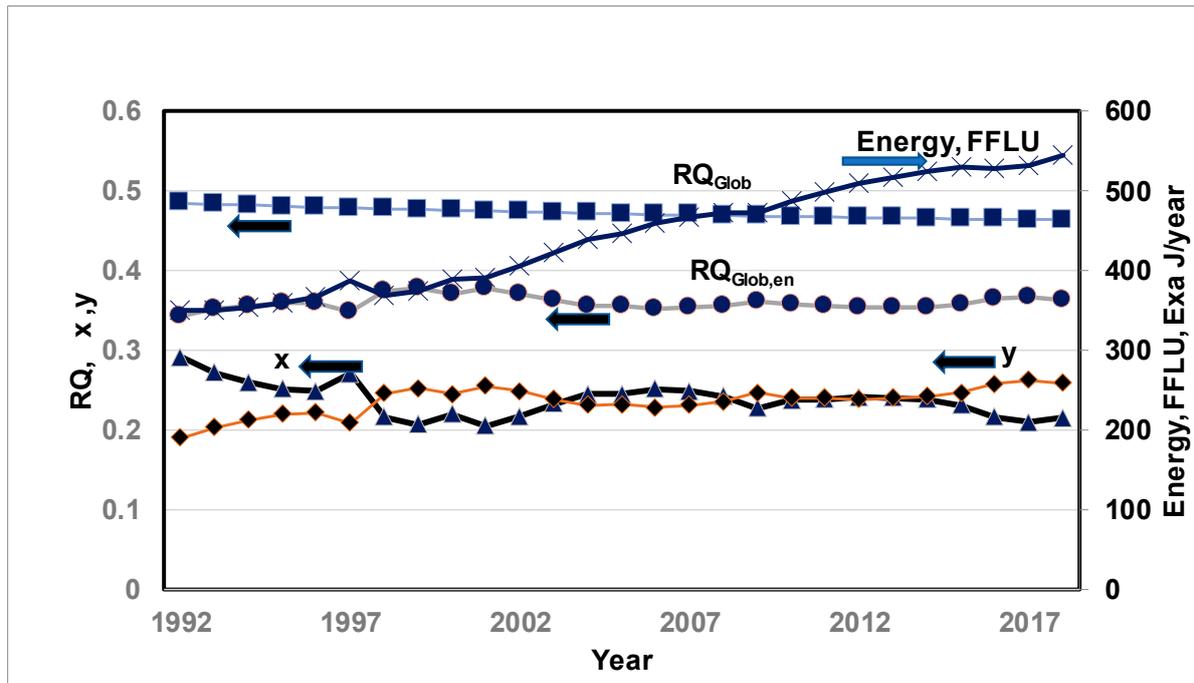


Figure 3. Predicted Variations in global respiratory quotient (■, RQ_{Glob} which is similar to ARQ in biology) and energy-based $RQ_{Glob(En)}$ (●), non-dimensional O_2 production (“x”, ▲), and non-dimensional CO_2 storage (“y”, ◆) from 1991 to 2020. Arrows ← indicate values on primary axis and → indicate values on secondary axis. “x” < 1, “y” < 1. FFLU energy based on the sum of FF energy consumption and LU energy estimated from LU- CO_2 emission quoted in Ref. [50]. Fossil emission data are from [57]. Land use data are from [54,58]. Figures on “x” and “y” are based on Quadratic Curve fit constants of Keeling’s data on CO_2 and O_2 in atm: (1991–2021).

The $RQ_{Glob(En)}$ of 0.36 is interpreted as the RQ of breathing, barren planet Earth (biomass and ocean free) as though it is breathing with one mole of O_2 as intake from the atmosphere for the oxidation of FFLU and releasing 0.36 moles of CO_2 into the atmosphere of Earth. See Ref. [59]. With $RQ_{Glob(En)} \approx 0.36$, and FFLU energy of 460.2 Exa J in the year 2006, the CO_2 added to the atmosphere in 2006 was $0.1 * 0.36 * 460.2 = 16.6$ GT.

4.2. Normalized O_2 Production (“x”) and CO_2 Storage (“y”)

Figure 3 shows the variations in dimensionless O_2 production (“x”) and O_2 storage (“y”) from 1991 to 2020. If the production of O_2 by biomass kept up with increased O_2 consumption by FFLU, then “x” should have remained constant, but the value of “x” decreased from 0.3 to 0.2 (i.e., 33% decrease), indicating that net O_2 from the atmosphere was depleted, indicating that biomass production could not compensate for increased oxygen consumption by FFLU. Hence, decreased “x” indicates net O_2 depletion from the atmosphere. Note that the CO_2 increased by 17% (from 354 ppm in 1991 to 414 ppm in 2020). There was increased photosynthesis and, hence, the C(s) added to biomass grew by 12% from 1982 to 2020 [13] due to CO_2 fertilization and, hence, O_2 production must have

grown by 12%. In spite of increased photosynthesis, the “x” decreased. The above results of increased photosynthesis with higher CO₂ concentration are supported by lab studies at Birmingham which indicated a 33% increase in O₂ when CO₂ was artificially increased to 565 ppm (current level 415 ppm) [60]. Another avenue of maintaining “x” is to protect existing trees, which have the potential to remove 228 GT of C from the atmosphere [61] and add 607 GT of oxygen (=228 * 32/12.01) (assuming RQ_{BM} = 1) to the atmosphere. The increased global temperature has a negative effect on “x” since it causes the plants to mature more quickly, thus reducing the period of photosynthesis.

The FFLU data for 1991–2020 show that energy released (or consumed by FFLU) increased by 60%, and hence, O₂ consumption must have increased by 60% due to FFLU, and CO₂ released must have increased by 60% at constant RQ_{FFLU}. However, the CO₂ in the atmosphere increased only by 14% (= (CO₂ in 2020 – CO₂ in 1991) * 100 / CO₂ in 1991), indicating that either the biomass growth served as an increased CO₂ sink and/or the ocean served as an increased CO₂ sink through storage.

Figure 3 shows that “y” has increased from 0.2 to 0.25 but “y” must remain constant if the storage rate of CO₂ increases in proportion to the increased O₂ consumption or increased CO₂ output by FFLU. Increased “y” indicates an increased uptake of CO₂ by ocean water, a lowered pH level of the ocean water, or a phenomenon known as ocean acidification. The pre-industrial level of pH was 8.2, and the current level is 8.1. Acidification affects PP, and the micro-organisms that fix carbon are less than efficient at fixing.

In order to understand the effects of CO₂ added to the atmosphere and, hence, on RQ_{Glob(En)}, consider the following cases. The discussions can be clarified by using Equation (9) for the following cases:

Case (I): if there is no biomass which could serve as a CO₂ sink, then x = 0.

$$RQ_{Glob(En)} = \left\{ \frac{CO_2 \text{ added to atm}}{O_2 \text{ by FFLU}} \right\} = RQ_{FFLU} - y \quad (21)$$

where RQ_{FFLU} = 0.78 (see Data section). Hence, the higher the ocean storage (y), the lower the RQ_{Glob(En)}; the average y is on the order of 0.23. Thus, RQ_{Glob(En)} = 0.55, a reduction of 32% essentially due to storage of CO₂ by the ocean.

Case (II): if there is no ocean storage, y = 0 and from Equation (9),

$$RQ_{Glob(En)} = RQ_{FFLU} - x * RQ_{LOWBM} \approx RQ_{avg} * (1 - x) \quad (22)$$

where RQ_{avg} = (RQ_{FFLU} + RQ_{LOWBM}) / 2 ≈ 0.9. The more O₂ production (i.e., “x”), the less the RQ_{Glob(En)}. The average x for the period 1991–2020 is 0.25, and hence, RQ_{Glob(En)} is on the order of (0.9 * 0.75) = 0.68, indicating a reduction of only 13% from RQ_{FFLU}. In addition, the ocean biomass does not add O₂ to the atmosphere while it acts, as more CO₂ sink as storage. In other words, ocean storage has a stronger effect on RQ_{Glob(En)}.

4.3. Earth’s Mass Loss, Earth’s Oxygen Concentration in the Future, and Tilt Angle

When FFs are mined in the solid state (e.g., coal) and liquid state (crude oil) and converted into a gaseous state (e.g., CO₂, H₂O) after oxidation, a part of CO₂ is stored by biomass and the oceans, and the remainder enters the atmosphere. Note that H₂O is returned to Earth in the form of rain. The mass of C(s) that enter the atmosphere with CO₂ gas is responsible for the mass loss from Earth. Using Equation (20), which presents {C(s)} in GT/Exa J released by FFs,

$$\dot{C}(s), \frac{GT}{Year} = F_{CEJ} * RQ_{Glob(En)} * \dot{E}_{FFLU}, F_{CEJ} = (M_C / HHV_{O_2}) = 0.0268 \quad (23)$$

where \dot{E}_{FLLU} in Exa J/year. See Row # 23, Table 2. Alternately, one can obtain a similar relation directly by determining the slope of CO₂ in Keeling’s curves:

$$\dot{C}(s), \frac{GT}{Year} = F_{CGt} * \left\{ \frac{d[CO_2]}{dt} \right\}, F_{CGt} = 10^{-6} * N_{air} * M_C = 2.13 \tag{24}$$

where N_{air} in Peta moles, $\left\{ \frac{d[CO_2]}{dt} \right\}$ (ppm/year), which is known from curve fits. Equation (24) requires knowledge of the slope of CO₂ with the year, while Equation (23) relies on the knowledge of $RQ_{Glob(En)}$, which is almost constant. Hence, the mass loss rate increases linearly with the annual energy consumption rate. The lower the $RQ_{Glob(En)}$, the lower the mass loss of the Earth and the higher the ocean acidity due to increased ocean CO₂ storage. With an increasing FFLU energy release rate, from 460 Exa J/year in 2006 to 544 Exa J/year in 2018, there is a rise in Earth’s mass loss rate from 4.4 GT/year in 2006 to 5.2 GT/year in 2018, revealing a total mass loss of about 52 GT within 12 years. Extrapolating the quadratic curve fit of Keeling’s data on CO₂ and O₂, and estimating the O₂ depletion rate from the atmosphere and the CO₂ addition rate to the atmosphere for another 2000 years, Table 5 shows the decrease in oxygen %, physiological effects, and predicted hypoxic years with Earth’s corresponding mass loss in GT { = (CO₂ in ppm at given year – CO₂ in ppm in year 1991) * 2.13}. Under extrapolation of the fit, the rate of decrease of O₂ in atm changes from –3.2 ppm/year (i.e. magnitude of depletion 3.2 ppm/year) in 1991 to –113 ppm/year and –186 ppm/year in the year 2900 and 3700 respectively (not shown in Table 5). Note that the Earth’s initial mass is 5.97×10^{12} GT. The first two columns are from data by OSHA [62], and the third column presents average O₂ % used in predicting the hypoxic year (within parenthesis); the fourth column on mass loss are estimated values. The estimations of hypoxic year when there is a 50% decrease in atmospheric O₂ concentration agree with predictions by Martin et al. [11], who used their extrapolation from parabolic fit to O₂ data over Canada. The recent literature on global water pumping {2150 GT, 1993–2010 with a total of 17 years, 126 GT/year} shows that Earth’s tilt of 4.4 cm/year is affected by Earth’s mass re-distribution [63,64]. Thus, the change in the moment of inertia of the Earth due to the mass loss of the Earth due to mining, particularly near the surface, which is far from the axis of rotation, may also affect the tilt angle. I

Even though Table 5 covers O₂ concentration from 21 % to 6 %, Ref. [12] warns that the decrease of O₂ from 21% to 19% is expected to cause serious health problems for BS including humans.

Table 5. Deoxygenation in atmosphere, physiological effects for humans, and predicted hypoxic year vs. O₂% and Earth’s mass loss based on extrapolation from quadratic fit to Keeling’s data.

O ₂ , % (v)	Physiological Effects for Humans	Avg O ₂ % (Predicted Year)	Cumulative Earth’s Mass Loss since 1991, GT (Year)
21	Normal	Avg O ₂ % = 21, (1991)	0 (1991)
19.5	Adverse effect, Oxygen-deficient	Avg O ₂ % = 19.5, (2600)	16,800 (2600)
16–19	Organ function fails, lack of coordination	Avg O ₂ % = 17.5, (2900)	36,100 (2900)
12–16	tachypnea (increased breathing rates), tachycardia (accelerated heartbeat),	Avg O ₂ % = 14.0 (3250)	67,700 (3250)
10–14	intermittent respiration, vomiting	Avg O ₂ % = 12.0 (3400)	84,300 (3400)
6–10	Lethal level of O ₂ at 62 millibar {called Armstrong limit at 6% sea level pressure}. Loss of consciousness, organ damage	Avg O ₂ % = 8.0 (3700)	123,000 (3700)

4.4. CO₂ Budget for Year 2006

Readers can skip Section 4.4, which shows the justification for assuming $z = 0.1$ in presenting the CO₂ budget for 2006, and move on to Section 4.5 for comparisons between

the annual results for the CO₂ budget with results from rigorous models with prescribed z . The CO₂ balance via the RQ method yields solutions for CO₂ stored in the atmosphere, CO₂ sink due to LBM and OWBM, and CO₂ stored in the oceans. The relations presented in Table 2 provide the CO₂ distribution through data input from Keeling's data on CO₂ and O₂ in the atmosphere and annual energy consumption. Only the CO₂ sink data by ocean biomass are not reported, while the current results estimate the total CO₂ sink due to both biomasses (LBM and OWBM). The CO₂ sink by LBM requires a knowledge of a split in O₂ added to the atmosphere by LBM and OWBM or a knowledge of the " z " fraction of O₂ produced by ocean biomass. A step-by-step procedure for the CO₂ budget using the RQ method is indicated in the supplement titled "Supp CO₂ budget Supp Step by Step CO₂ budget".

4.4.1. O₂ Production by Land and Controversy on O₂ Transfer from Ocean to Atmosphere and z Factor

Ref. [65] suggests that upper ocean water is a source of oxygen. Further, there is a periodic outflow of O₂ in the atmosphere during warm SS (equivalent to 4.5–5.6 GT of C or 12–14.9 GT of O₂) and an inflow from the atmosphere to the ocean in FW [66] But controversy exists about whether the ocean serves as a net oxygen producer or consumer when performing global C and oxygen balance.

Refs. [65,67] suggest that about 50% of oxygen accumulated on Earth originates from ocean PP through photosynthesis in upper 6% of ocean volume. The UN website [68] indicates that 50% of photosynthesis occurs on land, the other 50% in the oceans, and 25% of C is absorbed by the oceans. Others cite that the O₂ produced is about 50–70% of the total O₂ generated [69]. This statement refers only to oxygen currently in the atmosphere, i.e., O₂ stocks ($=0.21 * 1.77 \times 10^5 = 37,000$ Peta moles of O₂), 50% of which originated from biomass in the oceans (i.e., 18,500 Peta moles). The ocean storage is about 220 Peta moles (0.6% of atmospheric O₂) of dissolved oxygen. Thus, at first glance, $z \approx 0.5$ based on UN data, but this does not mean that all of the O₂ produced by OWBM is delivered to the atmosphere or that 50–70% of the air humans currently breathe in comes from the oceans. Skeptics argue [23] that the PP near the ocean surface (data at 20 m and 100 m in Ref. [24]) consume CO₂ and produce O₂, but MOM (which includes marine microbes and animals) consumes all of this oxygen, apart from dissolved oxygen, and produces CO₂. See also Ref. [70]. So, PP serves as a renewable nutrient or "fuel" for marine life; hence, there is no net O₂ delivered to the atmosphere or net CO₂ sink due to OWBM. However, the ocean is saturated with O₂ near the surface due to a high O₂ concentration in the atmosphere (21% O₂ or 210,000 ppm; it is much higher than CO₂, which is only about 400 ppm). Then, if PP produces O₂, it must supersaturate the O₂ near the surface, and if so, the extra O₂ produced by PP near the ocean surface may enter either the atmosphere or be circulated to deeper parts of the ocean. The global oxygen balance studies by Huang et al. [25] state that only 1.74 GT/year of oxygen enters the atmosphere from the ocean, while land-based biomass generates 16.01 GT/year, indicating about 10% of total O₂ from OWBM. See Appendix C, which presents another method of estimating z from the knowledge of C sink via land biomass. For the present study, z is treated as a parameter varying from 0 to 0.5 for comparing the CO₂ budget based on the RQ method with results from the literature data generated from more detailed models for 2006 and then selecting an appropriate value for " z ".

4.4.2. Effects of z on CO₂ Sink by LBM, OWBM, and Ocean Storage

It is shown that the RQ of the combined RQ for land and ocean biomasses (RQ_{LOWBM}) is affected by the value of " z " (Equation (14)) and, hence, depends on the energy (or O₂) fraction $\{z\}$ contributed by ocean-type biomass (Equations (14) and (15)) and $(1 - z)$ contributed by LBM. For the year 2006, the results for CO₂ distributions in GT/year and as a % of CO₂ emitted from the atmosphere, land, and ocean are shown in Figures 4 and 5 for $z = 0$, Figures 6 and 7 for $z = 0.1$, and Figures 8 and 9 for $z = 0.5$.

Results in these figures are shown for the following methods: (i) Linear fit of Keeling's data {Form.Lin} and (ii) Quadratic fits {Form.Quad} with constants summarized in data Section 3.4.2. Both of these results fall under the formula {Form} method; (iii) Keeling's data {Keel.atm} as it is for the year 2005–2006 (no curve fits, year-to-year basis), (iv) the literature data {Dat.atm} on % and GT/year for the atmosphere, land biomass, and ocean sink/storage. The method from (iii) is based on 2005–2006 data only and is subject to more errors due to fluctuating data from year to year. Most discussions are based on curve fit constants from the quadratic method and comparison with reported data. The last two lines in the figure captions give computed GT/year (quadratic method), while previous data are presented in parentheses.

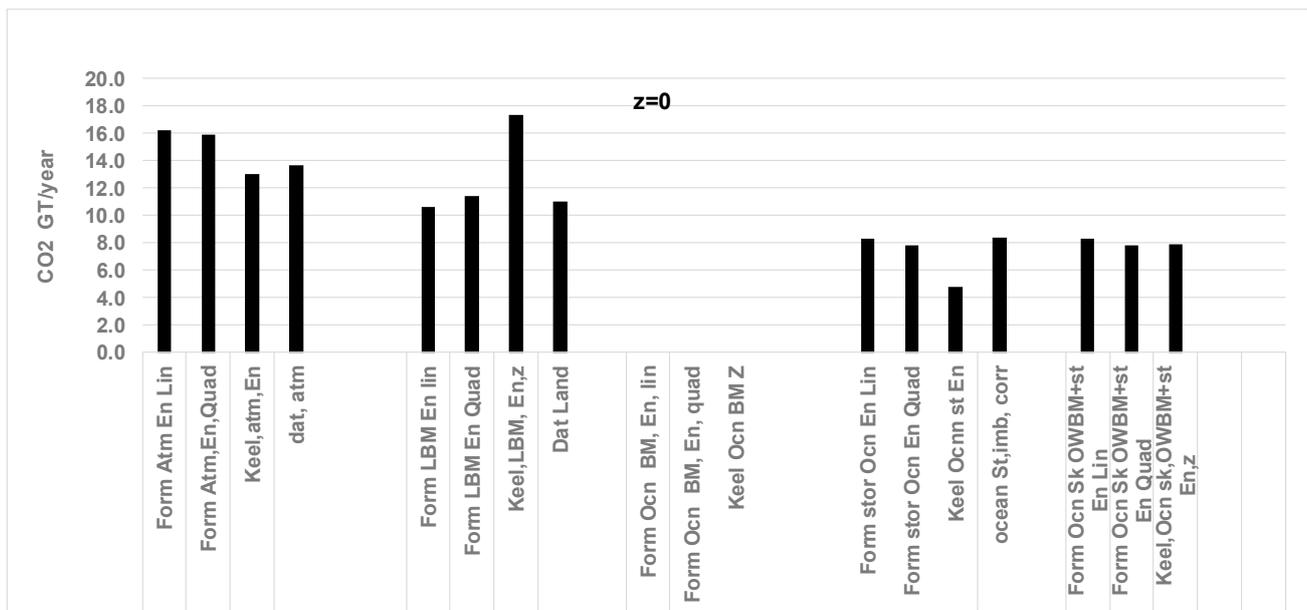


Figure 4. Comparison of results obtained from the RQ method and literature data for CO₂ (GT/year) sink by atmosphere, land, and ocean storage for the year 2006; $z = 0.0$, i.e., ocean biomass does not add O₂ to atmosphere. Data is from Ref. [50]. Atmosphere CO₂ data are from [53]. Ocean sink data are estimated from the average of several global ocean biogeochemistry models [44] and the ocean sink uncertainty of ± 0.5 GT C/yr. Total CO₂ by FFLU = 35.6 GT/year in 2006. Land sink data are from average of dynamic global vegetation models and uncertainty of ± 0.9 GT C/yr. Abbreviations in Chart: Form: Formula, ATM: atmosphere, En: Fossil and land use energy; data based on annual energy; Lin: Linear fit for CO₂ vs. year in Keeling's data; Quad: quadratic fit. The "Keel" data are based on 2006 Keeling's data in ppm for CO₂ added to atmosphere [46]; Data atmosphere: reported data from literature for atmosphere. Literature on CO₂ distribution is from [44]; LBM: land biomass, Ocn: Ocean, OWBM: ocean water biomass, Sk =Sink. Current results with the RQ method (previous data in parenthesis, Ref. [50]): all in GT of CO₂ /year, Atmosphere: 15.9 (13.7), Land 11.4 (11.1), Oceans St: 7.8 (8.4).

The results from Figures 4–9 can be summarized as follows:

- The results for CO₂ sink in the atmosphere are not affected by z .
- The ocean CO₂ storage is close to the reported data literature for all z ($z = 0, 0.1, 0.5$) and is a weak function of " z ". The reasons are as follows: the O₂ production by biomass is the difference between O₂ consumption by FFLU and actual O₂ removed from the atmosphere. Thus, once O₂ production is determined, the RQ_{LOWBM} of combined biomass from the land and ocean determines the amount of CO₂ sink, which is O₂ production * RQ_{LOWBM} . The RQ_{LOWBM} of combined biomasses is a weak function of z . The CO₂ balance dictates that the CO₂ storage (= CO₂ produced by FFLU – CO₂ sinks via combined land and ocean biomass) is a weak function of z .

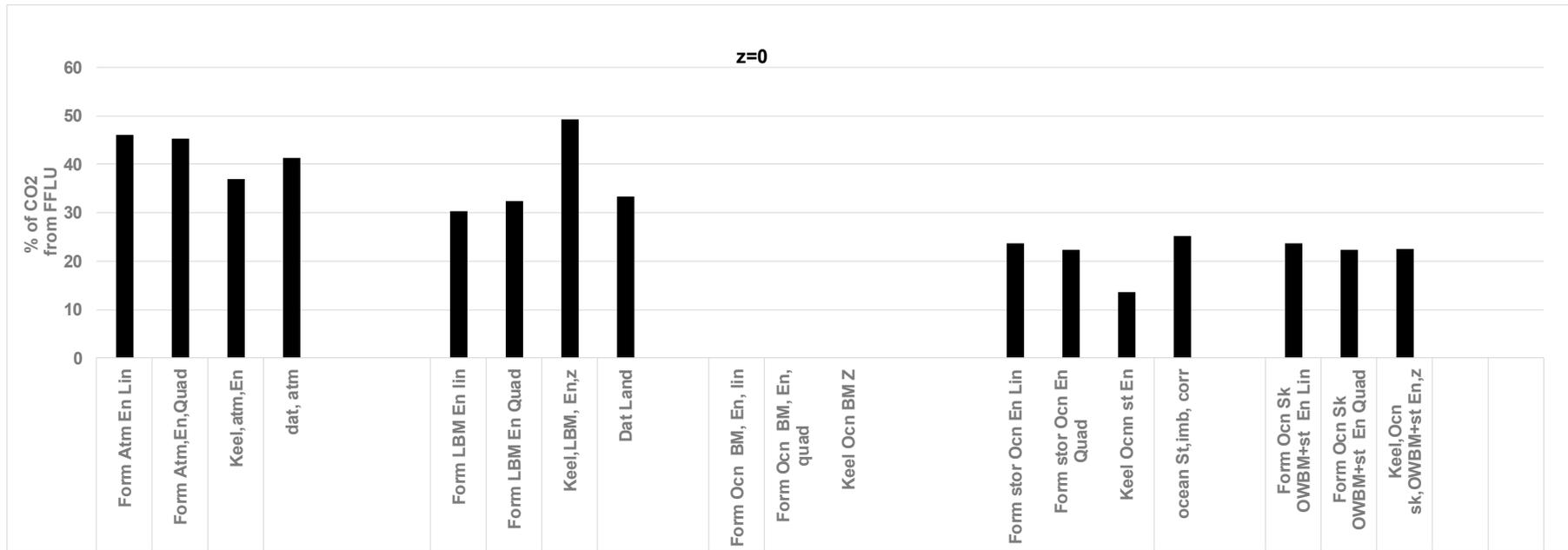


Figure 5. Comparison of results for the year 2006 obtained from the RQ method and literature data for CO₂ (%) sink by atmosphere, land, and ocean storage for the year 2006; z = 0.0, i.e., ocean biomass does not add O₂ to atmosphere. Data is from Ref. [50]. Atmosphere CO₂ data is from [53]. Z = 0.0, i.e., ocean supplies 0% of total O₂ while land supplies 100% of O₂. Data from Ref. [50] are for the quadratic fit for CO₂ and O₂. Abbreviations of terms on “X” axis explained in Figure 4 caption. Current results with the RQ method (previous data in parenthesis, Ref. [50]), in %: Atmosphere: 45.2 (41.3), Land 32.4 (33.4), Ocean St: 22.3 (25.3).

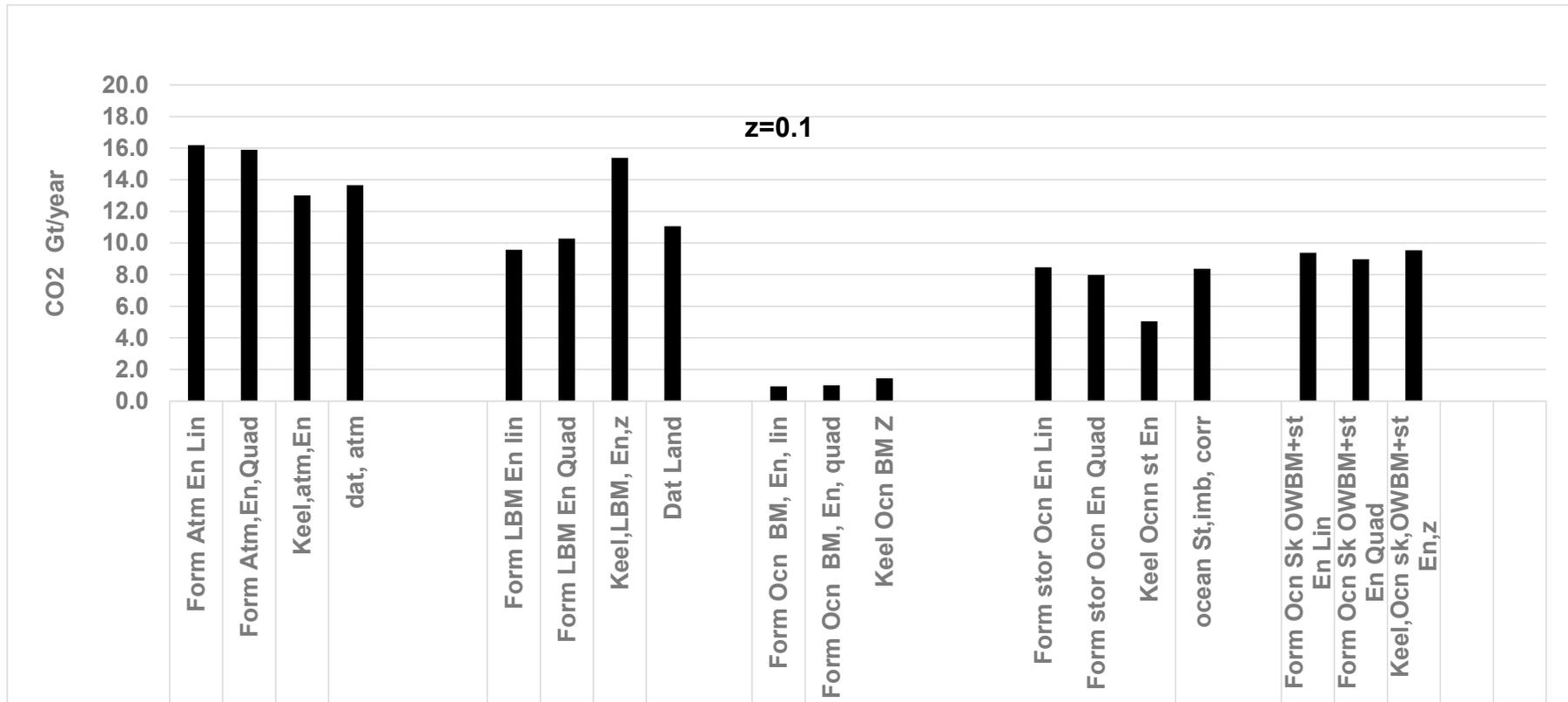


Figure 6. Comparison of results for the year 2006 obtained from the RQ method and literature data for CO₂ (%) sink by atmosphere, land, and ocean storage for the year 2006. Z = 0.1, i.e., ocean supplies 10% of total O₂ while land supplies 90% of O₂. Data is from Ref. [50]. Abbreviations of terms on “X” axis listed in Figure 4 caption. Keeling’s data on ppm CO₂ added to atmosphere [46]. Data atmosphere: reported data from literature for atmosphere. Literature on CO₂ distribution is from [44]. RQ_{FFLU} = 0.778, RQ_{LBM} = 1, RQ_{OWBM} = 0.87, RQ_{LOWBM} = 0.99 at z = 0.1. Current results with the RQ method (previous data in parenthesis, Ref. [50]): all in GT of CO₂ /year, Atmosphere: 15.9 (13.7), Land: 10.3 (11.1), Oceans St: 8.0 (8.4); error % less for ocean storage compared to results for z = 0.0; more error for land biomass compared to z = 0.

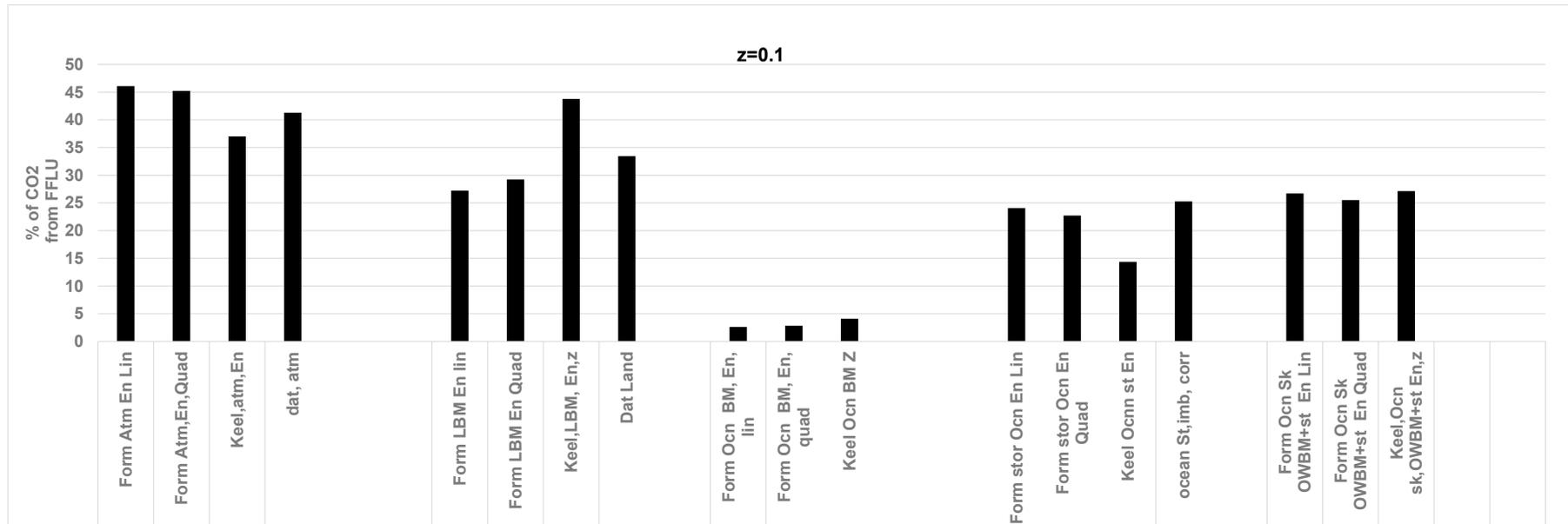


Figure 7. Comparison between the RQ method and previous data for CO₂ (%) sink by atmosphere, land, and ocean storage year 2006. Z = 0.1, i.e., ocean supplies 10% of total O₂% while land supplies 90% of O₂. Data is from Ref. [50]. Abbreviations are in charts. CO₂ by FFLU, year 2006 = 35.6 GT/yr. Abbreviations of terms on X axis explained in Figure 4 caption. $RQ_{FFLU} = 0.778$, $RQ_{LBM} = 1$, $RQ_{OWBM} = 0.87$, $RQ_{LOWBM} = 0.99$ at $z = 0.1$. Current results with the RQ method (previous data in parenthesis, Ref. [50]): all in %; Atmosphere: 45.2 (41.3), Land 29.2 (33.4), Ocean BM: 2.83, Ocean St: 22.7, (Ocn St + Ocn BM) = 25.53 (25.3).

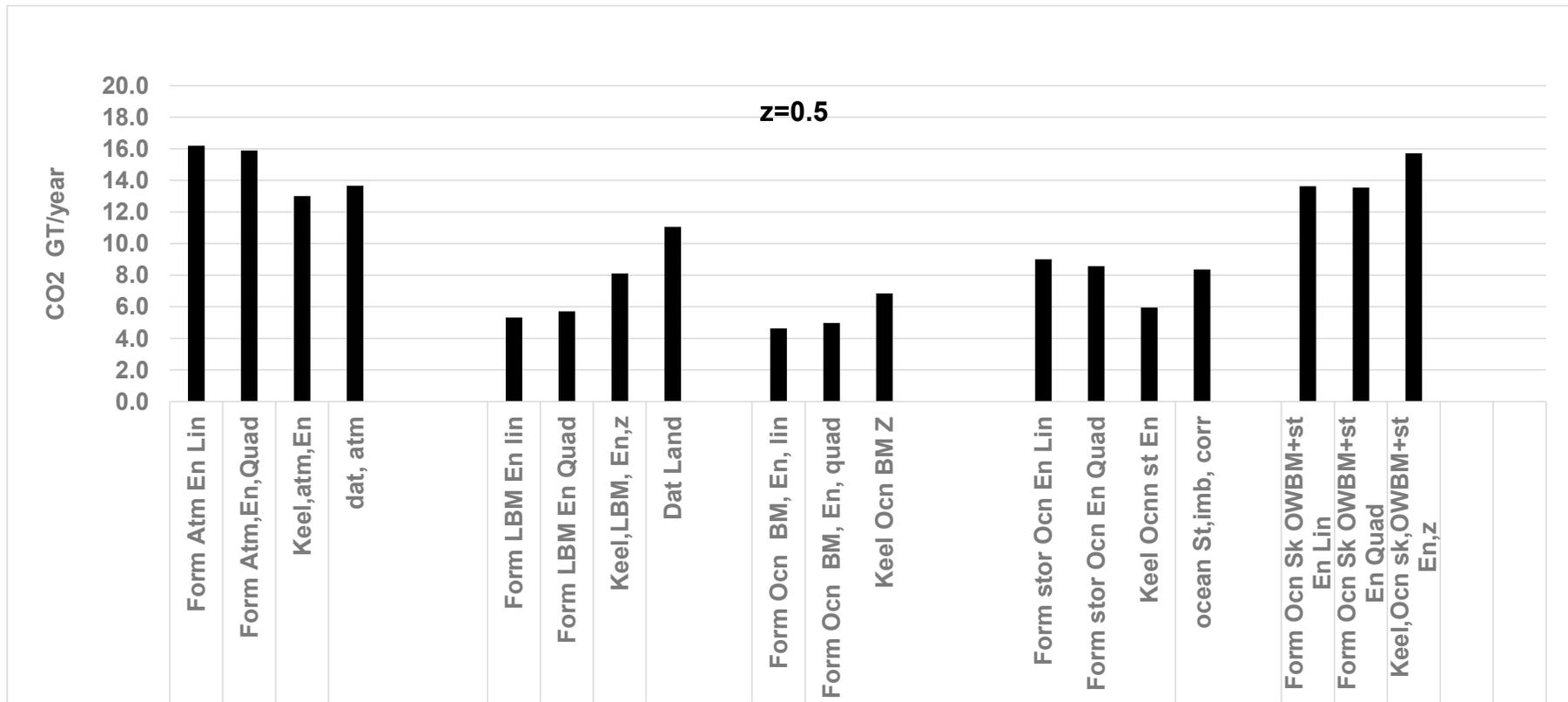


Figure 8. Comparison between the RQ method and previous data for CO₂ (GT/year) sink by atmosphere, land, and ocean storage; z = 0.5, i.e., ocean supplies 50% of total O₂ while land supplies 50% of O₂. Data is from Ref. [50]. Abbreviations of terms on X axis explained in Figure 4 caption. $RQ_{FFLU} = 0.778$, $RQ_{LOWBM} = 0.935$ at z = 0.5. Current results with the RQ method (previous data in parenthesis, Ref. [54]): all in GT of CO₂ /year, Atmosphere: 15.9 (13.7), Land: 8.1 (11.1), Oceans St: 8.6 (8.4). More errors for CO₂ capture by land due to high “z”.

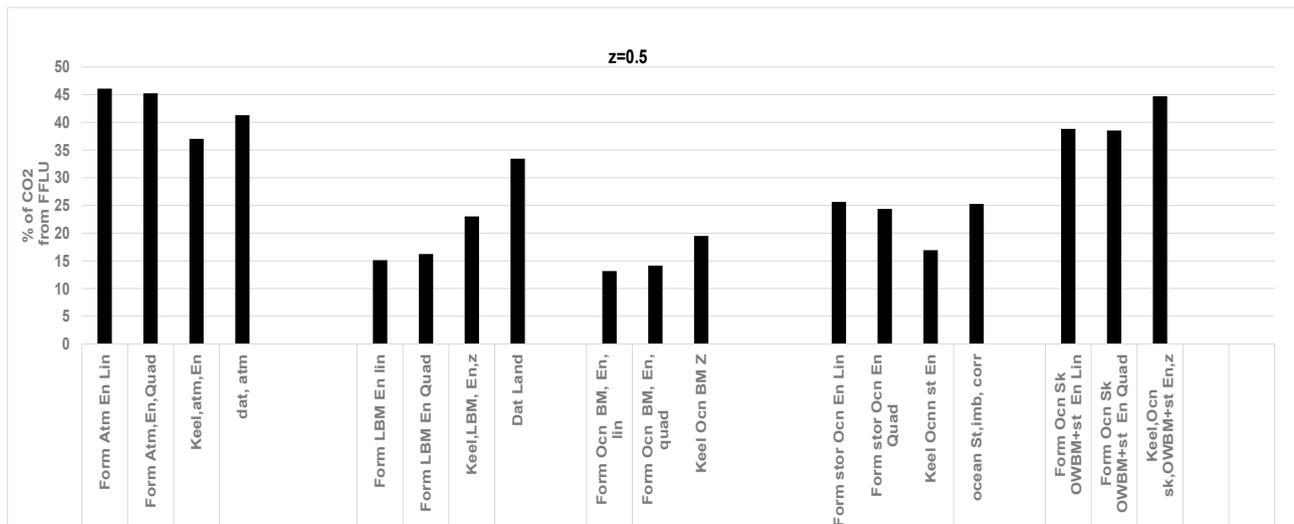


Figure 9. Comparison of CO₂ (%) obtained from the RQ method with the literature data for CO₂ (%) sink by atmosphere, land, and ocean storage; $z = 0.5$, i.e., ocean supplies 50% of total O₂ while land supplies 50% of O₂. Data areis from Ref. [50]. Abbreviations of terms on X axis explained in Figure 4 caption. $RQ_{LOWBM} = 0.935$ at $z = 0.5$. All in %; Atmosphere: 45.2 (41.3), Land 16.2 (33.4), Ocean St: 24.4 (25.3). More errors for land due to high z .

- c. There is a budget imbalance % in the previous literature data on C or CO₂, which is given as $[(FFLU\ CO_2\ source - CO_2\ added\ to\ the\ atmosphere - CO_2\ used\ by\ both\ land\ and\ ocean\ biomasses - CO_2\ stored\ by\ ocean\ water) * 100 / FFLU\ CO_2\ source]$. The imbalance is about 7% [50]. For example, the CO₂ added to the atmosphere is 15.9 GT/year, while data provided by the “stand-alone” atmosphere models indicate only 13.7 GT/year. However, the current formulation with the RQ method is based on the CO₂ or C balance method, i.e., the literature data reported on CO₂ must be increased by 7%, or data for atmosphere must be increased to 14.7 GT/year when compared with results from the RQ model.
- d. All the numbers were cross-checked by starting from the end results and back-calculating Keeling’s data (ppm of CO₂ added to the atmosphere and ppm O₂ removed from the atmosphere) for the following cases. (i) First estimate the ppm of CO₂ added to the atmosphere and O₂ removed from the atmosphere due to FFLU alone, in case there was no biomass or ocean storage in 2006; (ii) Then, estimate the ppm of CO₂ removed and O₂ produced by land and ocean biomasses (based on results for CO₂% removed by land and ocean biomasses) and re-calculate the ppm of CO₂ added to the atmosphere and O₂ depleted from the atmosphere. (iii) Finally, estimate the ppm of CO₂ removed due to storage by ocean water (based on % CO₂ stored by ocean water) and calculate the CO₂ added to the atmosphere. (iv) Verify these numbers (ppm/year) to be the same as Keeling’s data on CO₂ and O₂.
- e. Using the formula listed Table 2, the CO₂ fractions in the atmosphere, land and ocean BM, and ocean storage {Rows 11, 12 and 13} and the CO₂ loading in GT/year are estimated {Rows 3b,17 and 20}. The sum of the CO₂ fraction in the atmosphere, land and ocean BM, and ocean storage was confirmed to be in unity.
- f. The RQ method with a quadratic fit for land CO₂ sink is estimated as 10.3 GT/year at $z = 0.1$, while the reported data are 11.1 GT/year. The results from the RQ method agree closely with the literature data on CO₂ sink by LBM at low values of z ($0 < z < 0.1$).
- g. Since $RQ_{OWBM} = 0.87$, $RQ_{LBM} = 1$, then for $z = 0.1$, $RQ_{LOWBM} = 0.987 \approx RQ_{LBM}$ (since 90% O₂ added to atm is assumed to come from LBM).
- h. When $z = 0.5$ (50% O₂ by ocean biomass or 50% CO₂ by land biomass), the RQ method underpredicts the CO₂ sink by land biomass since the % of O₂ production

by land biomass is reduced with a corresponding reduction in CO₂ sink at a fixed RQ_{LBM}.

- i. When the explicit formula (Equation (14) to Equation (16)) was used for the year 2006 with $z = 0.1$, CO₂ atmosphere % = 45.2 (literature: 41.3), CO₂ land BM % = 29.04 (29.2), and (Ocn st + Ocn BM), % = 25.7 (25.3).

4.5. Comparison of Annual CO₂ from RQ Method with the Reported Annual Data (1991–2020)

The results for CO₂ storage in the atmosphere and ocean are very weak functions of z . Section 4.2 showed that the results on CO₂ sink via LBM were a strong function of z and when $z = 0.1$, the computed results agreed closely with reported data for the year 2006. In this section, RQ-based results for CO₂ sink via land, atmosphere, and ocean storage {solid lines Figure 10 (GT/year) and Figure 11 (%)} are compared with previously reported data {dashed line with marker} for atmosphere, land, and ocean storage, assuming $z = 0.1$. The agreement is very close. The data for the atmosphere fluctuates around the smooth curve due to year-to-year variations in wind conditions, temperature, and gradients of CO₂ between land and the atmosphere and ocean and the atmosphere. The predicted results reveal a smooth curve since the prediction is based on curve fit constants. Figure 12 (GT/year) and Figure 13 (%) show a comparison of computed CO₂ sink (solid line) by land biomass with previous data (dashed line with marker). The average C sinks from land and ocean sinks from 2000 to 2016 reported in [28] are 9.53 ± 2.57 and 5.59 ± 3.30 GT of CO₂/year (or 2.6 ± 0.7 and 1.5 ± 0.9 GT of C per year), while the RQ method shows CO₂ sink via ocean storage to be 5 to 10 GT /year with an average of 7.5 GT /year and land biomass to be 10.5 GT/year from 1991 to 2018. They are within the error bounds of Tohjima et al.'s work [28]. Ref. [28] also states that their sink estimates are within 1.47 GT/year, as presented by the GCP.

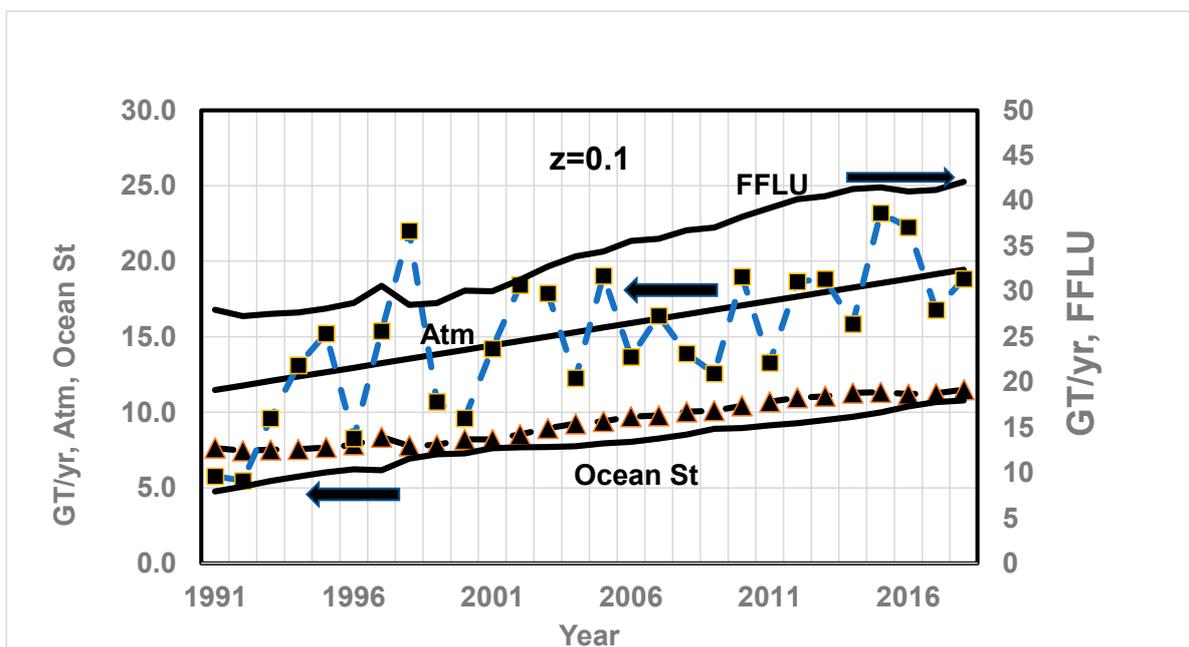


Figure 10. Comparison of CO₂ in GT/year since 1991 based on a quadratic fit of Keeling's data for CO₂ and O₂ and the RQ method (solid line) vs. literature results (dashed line with marker, ■ for atm, ▲ for Ocean st) for a; and ocean storage $z = 0.1$. Arrows ← indicate values on primary axis and → indicate values on secondary axis. Data are from Ref. [50]. See Figure 4 caption for data source. Results are weak function of z . The CO₂ stored in atmosphere and ocean storage shows an almost similar gradual increase. They are in proportion to CO₂ released in GT of CO₂ /year by FFLU. From Ref. [71], average for 1989–1998: CO₂ from FFLU = 28.9 GT of CO₂ /year; atmosphere: 12.1 and ocean storage = 8.4 GT of CO₂ /year.

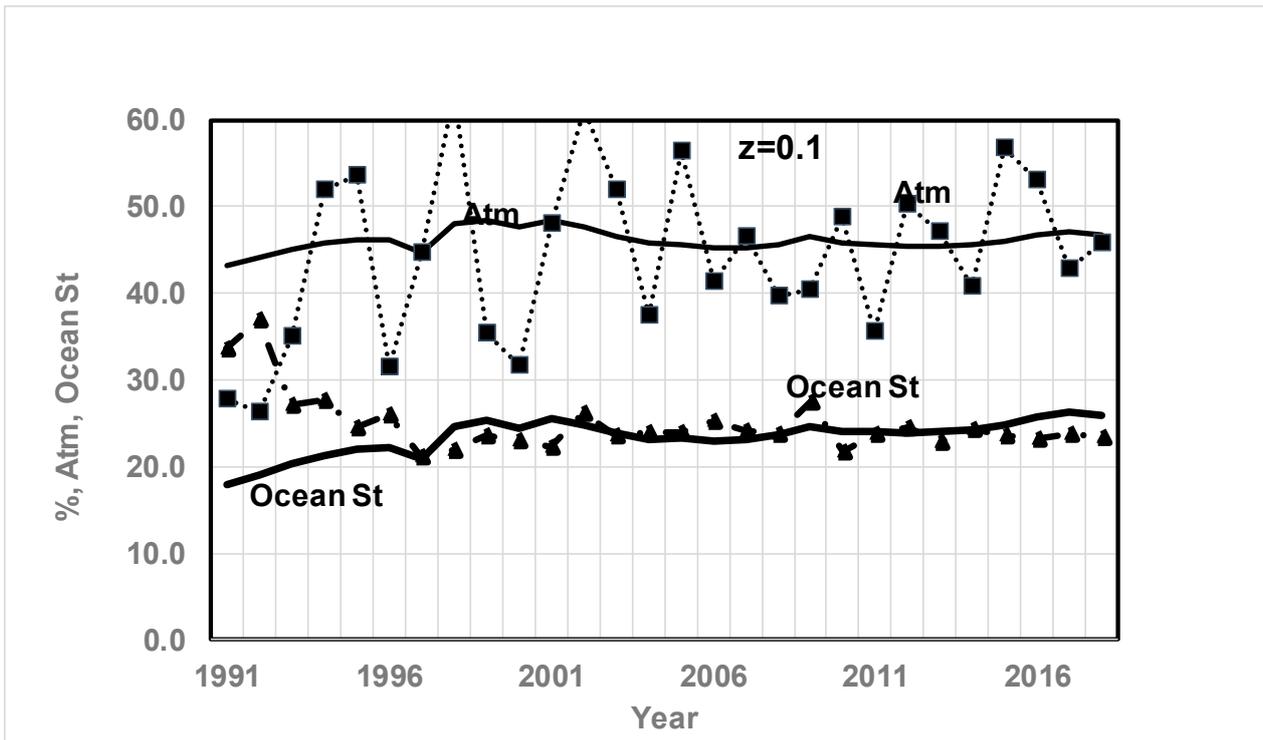


Figure 11. Comparison of CO₂% in atmosphere and ocean since 1991. Results based on quadratic fit of Keeling’s data for CO₂ and O₂ and the RQ method (solid lines without markers; thin line for atm, thick line for ocean storage) vs. previous results (dashed lines with marker, ■ for atm, ▲ for Ocean Storage) for atmosphere, and ocean storage ($z = 0.1$). Data is from Ref. [50]. See Figure 4 caption for data source. Results are a weak function of z . Atmospheric storage shows a slight increase in % while ocean storage shows a slight increase in %. From Ref. [71], average % from 1989 to 1998, atmosphere: 41.8%, and ocean storage: 29.1%.

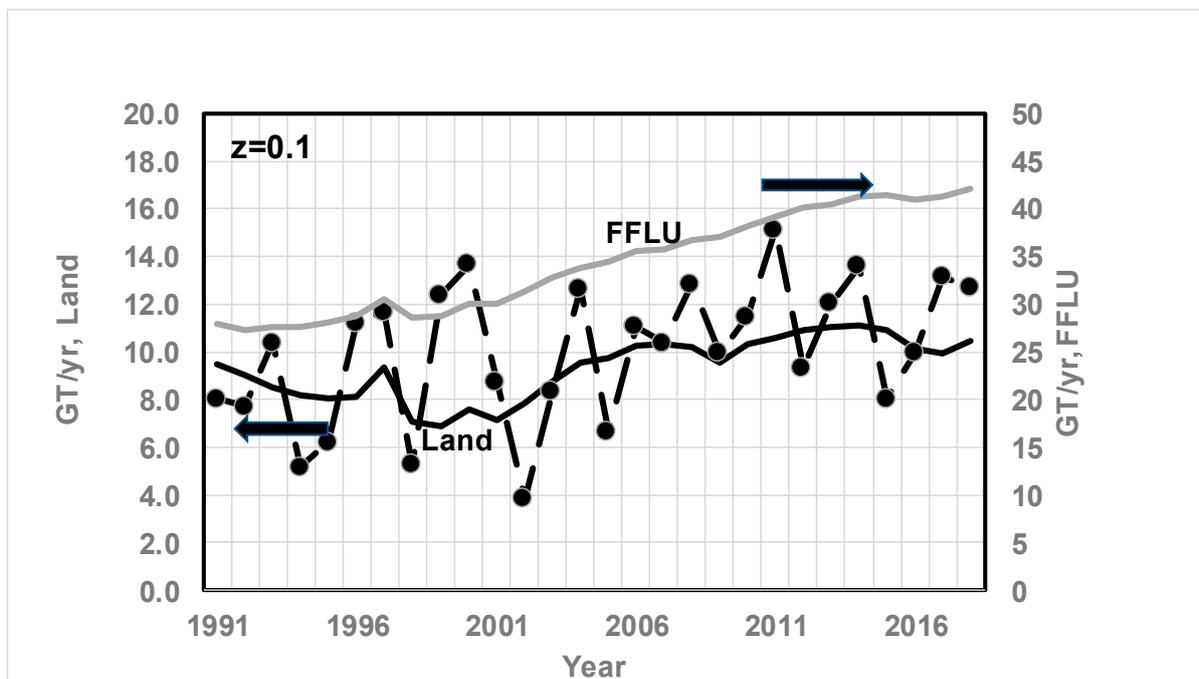


Figure 12. Comparison of CO₂ sink via land biomass (GT/year) since 1991 based on quadratic fit of Keeling’s data for CO₂ and O₂ and the RQ method (solid line) vs. literature data (dashed line with

marker, • for Land literature data) for atmosphere and ocean storage ($z = 0.1$). Arrows ← indicate values on primary axis and → indicate values on secondary axis. Data are from Ref. [50]. GT/ of CO₂ year seems to increase due to CO₂ fertilization. See Figure 4 caption for data source. Results are a strong function of z . From Ref. [71], average for 1989–1998: FFLU = 28.9 GT/year; land 8.4.

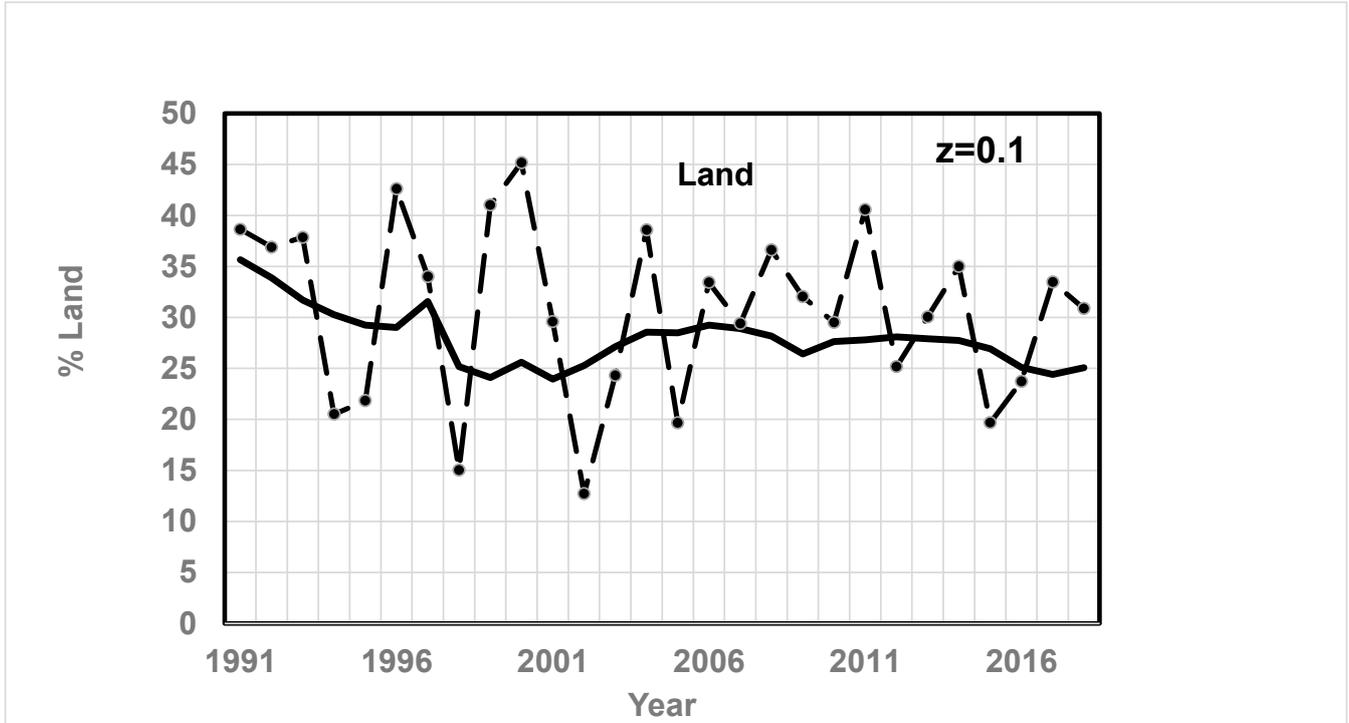


Figure 13. Comparison of CO₂% since 1991 based on quadratic fit of Keeling’s data for CO₂ and O₂ and the RQ method vs. literature results (dashed line with marker, • for Land literature data) for land biomass ($z = 0.1$). Data is from Ref. [50]. See Figure 4 caption for data source. Results are a strong function of z . From Ref. [71], average % from 1989 to 1998 of land: 29.1%. However, Bonan reports 45% of the organic carbon on land in their biomass and soil [72].

4.5.1. Freezing CO₂ Growth in Atmosphere Using RQ

One can estimate the desired RQ_{FFLU} so that CO₂ in the atmosphere remains flat or $d(\text{CO}_2)/dt = 0$ in Equation (9). See Appendix B for details.

$$RQ_{FFLU} - RQ_{LOWBM} * x - y == \frac{\left\{ \frac{d(\text{CO}_2)}{dt} \right\} \left(\frac{\text{ppm}}{\text{year}} \right) * F_{Bal}}{\dot{E}_{FFLU}} = 0. \tag{25}$$

Required RQ_{FFLU}: Solving for RQ_{FFLU} from the above equation,

$$RQ_{FFLU} = RQ_{LOWBM}x + y \tag{26}$$

where x is given by Row 7a, Table 2 in terms of annual energy release rate from FFLU, and Row 7b, Table 2 in terms of annual carbon release rate from FFLU and $[d(\text{O}_2)/dt]_{\text{atm}}$.

It is noted that “ y ” remains almost flat (Figure 3), indicating increased CO₂ storage (hence, ocean acidity) in proportion to O₂ consumption rate by FFLU or annual energy release rate from FFLU. Since CO₂ remains flat, the coefficients d_2 , d_1 , and d_0 for quadratic fit of O₂ data may be different; hence,

$$\frac{d[\text{O}_2]}{dt} = 2 * e_2 + e_1 \tag{27}$$

Figure 3 reveals that variations in x and y are mostly flat ($x \approx 0.3$ to 0.2 , $y \approx 0.2$ to 0.25) compared to FFLU energy, which increases by 60%. Assuming $x \approx 0.25$, $y = 0.23$, $RQ_{LOWBM} = \approx 1$, the desired $RQ_{FFLU} = 0.48$, $y = 0.23$ (with ocean acidification), and $RQ_{FFLU} = 0.25$ (with no ocean acidification, $y = 0$). The low value of 0.25 for RQ_{FFLU} is difficult to achieve in practice since the lowest RQ is 0.5 for methane fuel (or natural gas).

Required RQ_{LOWBM} : If RQ_{FFLU} is fixed, one may solve for the desired RQ_{LOWBM} as (Equation (26))

$$RQ_{LOWBM} = \left\{ \frac{RQ_{FFLU} - y}{x} \right\} \quad (28)$$

If NG is used as a global fossil fuel, the $RQ_{FFLU} = 0.5$, and assuming $x = 0.25$, $y = 0.23$, the desired $RQ_{LOWBM} = 1.08$. Ref. [73] reports an RQ from 1.2 to 2.0 (i.e., PQ as 0.5 to 0.85) for sea weeds. Another avenue for increasing CO_2 sink via biomass is to use AI photosynthesis and photoelectrochemical carbon sinks [74].

4.5.2. Freezing CO_2 Growth in Atmosphere by CO_2 Storage

Carbon Capture and storage: If direct air capture (DAC) technologies are adopted for extracting CO_2 directly from the atmosphere, the required underground storage of CO_2 , $\dot{N}_{CO_2,St,UG}$, is given as

$$\dot{N}_{CO_2,St,UG} = \dot{N}_{CO_2,St,atm} = \left\{ \frac{d[CO_2]}{dt} \right\} \left(\frac{ppm}{year} \right) * 10^{-6} * N_{air} \quad (29)$$

where $\dot{N}_{CO_2,St,UG}$ in Peta moles/year. The required amount of C(s) to be sequestered in mass units is given as

$$\dot{m}_{C(s),St,UG} = \dot{N}_{CO_2,St,UG} * M_C = F_{CGt} * \left\{ \frac{d[CO_2]}{dt} \right\}_{atm} \quad (30)$$

$$\dot{m}_{CO_2,St,UG} = \dot{m}_{C(s),St,UG} \frac{M_{CO_2}}{M_C} = \dot{m}_{C(s),St,UG} * 3.66$$

where $\dot{m}_{C(s),St,UG}$, $\dot{m}_{CO_2,St,UG}$ are the required amounts to be stored in GT of C(s) and GT of CO_2 per year in the underground (UG) storage for maintaining $\{d[CO_2]/dt\}$ in the atmosphere = 0. See Row #3b, Table 2.

Several models exist for underground gas storage [75,76]. One can use depleted oil/gas reservoirs as CO_2 underground storage with the additional benefit of reducing Earth's mass loss rate [9] since CO_2 mass, which would have escaped to the atmosphere, is returned to Earth with underground storage.

4.6. Relation between Global Temperature, Rate of Heating, Energy, and Global CO_2 Concentration

The authoritative NASA website contains data on land and sea surface temperature (SST) [32]. Most of the data are reported as temperature anomalies, defined as the difference between local temperature and average temperature or base temperature for the specific period of 30 years (1951–1980) at the same location, so the temperature anomaly is location-independent. The global average temperature for 30 years was $13.9^\circ C$ or $57^\circ F$ [77]. The 2010 global temperature was $14.7^\circ C$, or $0.8^\circ C$ was the temperature anomaly in 2010. For additional information, see websites at NASA's Goddard Institute for Space Studies and NOAA's National Centers [78].

The quadratic curve fit to the global average temperature since 1880 computed from the temperature anomaly and assuming a global 30-year average (1951–1980) temperature of $13.9^\circ C$ ($57^\circ F$) [79] yields the following relation:

$$T^\circ C = g_2 t^2 + g_1 t + g_0, R^2 = 0.903, years : 1880 - 2023 \quad (31)$$

where $g_2 = 9.114 \times 10^{-5}$, $g_1 = -5.281 \times 10^{-3}$ t, $g_0 = 13.71$, $t = \text{Year of interest} - 1880$,

$$\frac{dT}{dt}, \left(\frac{^{\circ}\text{C}}{\text{Year}} \right) = 2 g_2 * t + g_1 \quad (32)$$

Based on curve fit constants, the heating rate was $0.15 \text{ }^{\circ}\text{C}/\text{decade}$ (1981–1991), and now it has jumped to $0.22 \text{ }^{\circ}\text{C}/\text{decade}$ (2012–2022).

Since data are available for both the global average temperature vs. year and Keeling's data on CO_2 ppm, it is of interest to plot temperature vs. CO_2 concentration, which is related to energy from FFLU. Selecting T_0 for year 1991, the ΔT was then plotted against $([\text{CO}_2]/[\text{CO}_{2,0}])$ where $[\text{CO}_2]$ was the CO_2 concentration in the year of interest and $[\text{CO}_{2,0}]$ was the concentration of CO_2 in the year 1991 (Figure 14). The curve fits for ΔT vs. $[\text{CO}_2]/[\text{CO}_{2,0}]$ for years 1991–2022 (Figure 14) yields

$$\Delta T, ^{\circ}\text{C} = h_1 \left(\frac{[\text{CO}_2]}{[\text{CO}_{2,0}]} \right) + h_0, h_1 = 4.0, h_0 = -4.10, [\text{CO}_{2,0}] = 351 \text{ ppm}, R^2 = 0.86 \quad (33)$$

Note that the concentration ratio $([\text{CO}_2]/[\text{CO}_{2,0}])$ is the same as the GT ratio of CO_2 . Differentiating Equation (33), the rate of temperature rise is given as

$$\frac{dT}{dt} = \frac{h_1}{[\text{CO}_{2,0}]} \left(\frac{d[\text{CO}_2]}{dt} \right)_{atm}, h_1 = 4.0 \quad (34)$$

where $\{d[\text{CO}_2]/dt\}_{atm}$ in ppm/year and one may use linear or quadratic fit to obtain the slope $\left(\frac{d[\text{CO}_2]}{dt} \right)_{atm}$.

Row #21a, Table 2 for global temperature rise ΔT vs. year.

Row #21b, Table 2 for global temperature rise ΔT vs. $[\text{CO}_2]/[\text{CO}_2]_0$.

Row #22a, Table 2 for rate of temperature rise dT/dt in terms of $\left(\frac{d[\text{CO}_2]}{dt} \right)_{atm}$.

Ref. [1] reports $0.0125 \text{ }^{\circ}\text{C}/\text{year}$ (or $0.125 \text{ }^{\circ}\text{C}$ per decade, around 1994) with a CO_2 increase of 2 ppm/year, while Equation (34) with 2.08 ppm/year (Keeling's data, linear fit) yields $0.023 \text{ }^{\circ}\text{C}/\text{year}$ or $0.23 \text{ }^{\circ}\text{C}/\text{decade}$. The NASA website [77] indicates $0.15\text{--}0.20 \text{ }^{\circ}\text{C}/\text{decade}$ since 1975, while the recent data in 2022 indicates $0.18 \text{ }^{\circ}\text{C}/\text{decade}$ [80].

In the following, an attempt has been made to relate the rate of heating of Earth to the annual energy release rate $\{\dot{E}_{FFLU}, \text{Exa J}/\text{year}\}$, even though the processes governing the relation are complex (see Ref. [36] for balance equations). Using the definition of $RQ_{\text{Glob(En)}}$, one can express $d[\text{CO}_2]/dt$ in the atmosphere as

$$\left(\frac{d[\text{CO}_2]}{dt} \right)_{atm} = F_{\text{CO}_2} * RQ_{\text{Glob(En)}} * \dot{E}_{FFLU}, F_{\text{CO}_2} = \left(\frac{10^6}{N_{air} * HHV_{O_2}} \right) = 0.0126 \quad (35)$$

Figure 3 shows that $RQ_{\text{Glob(En)}}$ is almost constant. Hence, the above equation suggests that the rate of CO_2 increase in the atmosphere (ppm/year) is proportional to \dot{E}_{FFLU} . Expressing Equation (35) in Equation (34), the rate of heating is given as

$$\frac{dT}{dt} = F_{dTdt} * RQ_{\text{Glob(En)}} * \dot{E}_{FFLU}, F_{dTdt} = \left\{ \frac{h_1 * F_{\text{CO}_2}}{[\text{CO}_{2,0}]} \right\} = 1.44 \times 10^{-4} \quad (36)$$

which shows that the rate of temperature rise is proportional to the energy release rate in Exa J per year.

Row #22b, Table 2 for the rate of temperature rise dT/dt in terms of $RQ_{\text{Glob(En)}}$ and energy release rate.

While the relation for dT/dt with $d[\text{CO}_2]/dt$ has a slope of 4 (Equation (34)), Equation (36) indicates the weaker relation of dT/dt with the annual energy release rate. The cumulative energy release from 1991 to 2018 (total of 27 years) via FFLU was about 12,000 Exa J added to Earth (which is almost 40 times more than FFLU energy in 1991), while 4500 GT of CO_2

was added to the atmosphere (which is almost two times the amount present in 1991) during the same period, resulting in the greenhouse effect. Typically, the greenhouse effect is dominant compared to the waste heat/energy release effect.

With 2018 data on $\dot{E}_{FFLU} = 545$ Exa J/year, $RQ_{Glob(En)} = 0.36$ from a quadratic fit, Equation (36) yields $dT/dt = 0.027$ °C/year or 0.27 °C/decade. If a linear fit is adopted, $RQ_{Glob(En)} = 0.30$, $dT/dt = 0.023$ °C/year or 0.23 °C/decade. The estimate obtained from the RQ method for Keeling’s curves agrees with the heating rates of 0.28 °C/decade (after 2010) and 0.18 °C per decade (1970–2010) [81], which are based on satellite remote sensing data. The same reference cites similar heating rates by the GCP.

Figure 14 yields the following additional relations:

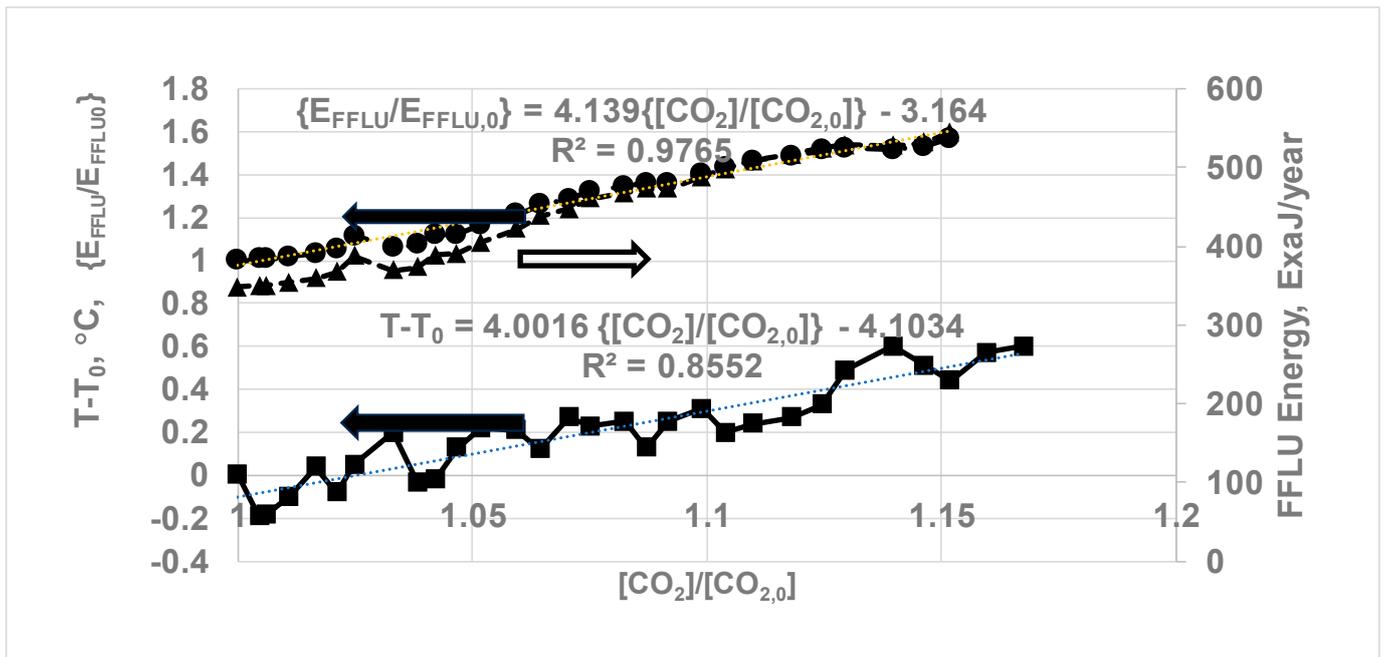


Figure 14. Variations in global temperature difference ($T - T_0$) (■), FFLU energy release rate (▲), and normalized Energy release $\frac{\dot{E}_{FFLU}}{\dot{E}_{FFLU,0}}$ (Symbol ●), with normalized CO_2 concentration, $[CO_2]/[CO_{2,0}]$ (1991–2020); $[CO_2]$ atmosphere. Arrows ← indicate values on primary axis and → indicate values on secondary axis. Concentration in ppm in any given year and $[CO_{2,0}]$ atmosphere CO_2 concentration in 1991. Energy and CO_2 data are from Ref. [50]. Global temperature data are from [82]. See data for temperature of NY City in Ref. [83]. The energy release by FFLU (secondary axis), and normalized energy release (primary axis). There are 18% and 60% increases in energy release rate in the years 2006 and 2018, respectively, compared to year 1991.

The normalized energy release rate and hence the normalized CO_2 concentration have the following fits:

$$\frac{\dot{E}_{FFLU}}{\dot{E}_{FFLU,0}} = i_0 + i_1 \frac{[CO_2]}{[CO_{2,0}]}, \text{ Or } \frac{[CO_2]}{[CO_{2,0}]} = \left(j_0 + j_1 \frac{\dot{E}_{FFLU}}{\dot{E}_{FFLU,0}} \right), i_0 = -3.16, i_1 = 4.14, j_0 = 0.76, j_1 = 0.24 \quad (37)$$

$$R^2 = 0.98$$

4.7. Limitation of Results

The CO_2 budget results with the RQ method are based on the presumption that Keeling’s data on CO_2 and O_2 in the atmosphere are affected by CO_2 sources from FFLU and CO_2 sinks by biomass and CO_2 storage in the oceans. Thus, if there is an increasing global temperature, it would be reflected in less CO_2 sink by biomass and less O_2 production and vice versa, which are reflected in Keeling’s data. The results do seem to be comparable to the reported literature data, which are based on more detailed fundamental and stand-

alone models for the atmosphere, land, and oceans. The results in Table 5 on global O₂ concentration and mass of earth vs. year are based upon the extrapolation of quadratic fit to Keeling's data as though CO₂ distributions continue the same trends, and they are independent of global temperature and increasing CO₂ concentrations and sea levels.

4.8. Policies and Econometry

Policies: Economic growth measured in terms of a nation's GDP (gross domestic product) is intricately coupled with the growth of energy consumption. If the source of energy is from the combustion of fossil fuels, the higher the GDP, the higher the energy consumption and the more CO₂. The Intergovernmental Panel on Climate Change (IPCC) recommends climate action via policies limiting global warming to 1.5 °C, which requires a quantum leap in policies to reduce the slope of [CO₂] vs. year. The benefits of CO₂ reduction vs. the cost of policies and the social cost of carbon (SCC), a dollar measure of the "cost" damage to society as a result of CO₂ added to the atmosphere, were investigated by Fraas et al. [84]. The cost of promoting clean technology and net zero emissions must be balanced against the SCC.

The policies require changes in the "upstream" and "downstream" of CO₂ production.

Upstream: (i) Mandates for utilities to adopt low-carbon FFs in electricity generation by a specified deadline, (ii) recommendation on "layered" tax and increased excise taxes, based on the RQ of FFs (a measure of CO₂ emission in tons per unit energy release, e.g., coal with RQ = 1 vs. NG with RQ = 0.5), (iii) use of Ref. [47] in estimating the reduced RQ for a mix of FFs and renewable fuels (RFs) (e.g., gasoline-ethanol blend) and added incentives along with reduced taxes for RFs, and (iv) promotion of solar power.

Downstream: (i) Cap-and-trade regulations, (ii) tax incentives for mitigation, (iii) CO₂ per kWh (which involves efficiency and an increase in cost of electricity generation when meeting mandates) and carbon taxes; e.g., Sweden: USD 30 per ton of CO₂ in 1991 and increased to USD 132 [85], (iv) carbon capture and storage (CCS) and approximate estimation of C to be sequestered using the relations provided in the current text, (v) emissions trading systems with high USD cost of CO₂ per ton, indicating the extent of enforcement of the Paris accord and vice versa, (vi) CO₂ tax based on actual CO₂ emissions rather than transport vehicle weight estimated from the RQ value of fuels [6] and actual fuel consumed, (vii) residential and industrial non-electricity FFs use (e.g., home use for heating and cooking, shops and offices).

Cost: Cost has been identified as the major barrier to implementing CO₂ capture and storage or utilization technologies [86]. Higher adoption of CO₂ capture technologies in various heavy industries will be based on the carbon tax credits and policy framework across different countries [87]. It should be noted that the Internal Revenue Code (IRC) Section 45Q of the US tax code provides tax credits for qualified carbon dioxide captured and sequestered. However, additional policies around the transportation of captured carbon, storage, and taxation of unabated carbon dioxide should be enacted for large-scale implementation of the CO₂ capture technologies and negative or positive outcomes [88,89].

5. Summary

The power plants breathe in O₂ from the atmosphere, oxidize FFs and breathe out CO₂. The RQ_{FF} varies from 0.5 (NG) to 1.0 (coal). Global RQ is expressed in two forms: (I) RQ_{Glob} (= CO₂ added to the atmosphere/O₂ depleted from the atmosphere), which is at about 0.47, and (II) RQ_{Glob(En)} (= CO₂ to the atmosphere/O₂ consumed by FFLU from the atmosphere), which is about 0.36. The definition of RQ_{Glob(En)} leads to an estimation of CO₂ in GT in the atmosphere per Exa J released by FFLU = 0.1 * RQ_{Glob(En)}. If RQ_{Glob} or RQ_{Glob(En)} decreases, this indicates less CO₂ in the atmosphere and higher CO₂ storage and, hence, increased acidity of the oceans. The RQ_{Glob(En)} of 0.36 implies that 0.36 moles of CO₂ are added to the atmosphere for every mole of O₂ used by FFLU in releasing energy. The CO₂ release by FFLU increased from 27 to 42 GT/year by FFLU for the period 1991–2020.

The simple RQ method of analysis of Keeling's data leads to explicit formulae for CO₂ sinks in the atm, land and ocean biomasses, and storage in the oceans. The computed results with a quadratic curve fit agree with most of the reported data for CO₂ sink via land biomass (GT per year and %) for the year 2006 when z (the ratio of O₂ contributed by the ocean to the atmosphere/total O₂ contributed by both land and ocean biomasses) is selected to be about 0.1. Computed results for CO₂ storage in the atmosphere and ocean are weak functions of z and agree closely with the collected data.

The RQ concept is extended for the period of 1991–2020 for estimating the annual CO₂ distribution in GT/year and as a % of CO₂ produced by FFLU by assuming $z = 0.1$. The RQ-based results are then validated with the literature data (1991–2020) generated using a rigorous model, which includes the effects of wind velocity, temperature, and gradients of CO₂ (i) between land and the atmosphere and (ii) ocean and the atmosphere, and ocean circulation and temperature; thus, the data fluctuate from year to year. However, the predicted results for CO₂ sinks reveal a smooth curve, since the prediction is based on curve fit constants. The RQ method using Keeling's data shows the variations in CO₂ sink by the atmosphere, land, and ocean as follows: 12 to 33 GT/year (atmosphere), 8 to 10 GT/year (land biomass), and 5 to 10 GT/year as storage in the oceans.

If slow, gradual extinction is a part of the evolution of life on Earth, the planet seems to be marching towards slow extinction due to the time lag between the development of human traits and the fast-changing local climate affected by increasing CO₂ concentration. Just as in biology where nutritional "therapy" is used to control RQ and reduce acidity in the blood, the FFs "therapy" requires low RQ fuels and high RQ biomasses. The sargassum (seaweed) has an RQ of 1.2 to 2.0 [9,73]. The rate of temperature rise with the change in CO₂ concentration is presented, and Keeling's data seem to suggest a 0.23 °C rise per decade, while NASA's data indicate a 0.15–0.20 °C rise per decade.

6. Future Work

It was shown that the warming causes an increasing vapor pressure deficit (VPD) {difference between the saturation pressure of H₂O in the atmosphere, $P^{\text{sat}}_{\text{H}_2\text{O}}$, which increases with temperature, and actual vapor pressure over land and the oceans ($p_{\text{H}_2\text{O}}$)} within the globe, creating plant stress, soil drought, and reducing the life span of vegetation [90]. The impact of the VPD on atmospheric pressure, wind velocity, rain, and hurricanes must be studied. Algae (chemical formula: $(\text{CH}_2\text{O})_{106}(\text{NH}_3)_{16}(\text{H}_3\text{PO}_4)$ or $\text{C}_{106}\text{H}_{263}\text{N}_{16}\text{O}_{10}\text{P}$ including PP) can serve as a renewable fuel and can minimize the use of FFs for energy.

It is noted that the control of pollutant emissions sometimes results in global warming in addition to CO₂. The white reflective clouds formed when SO₂, a pollutant, is mixed with water vapor reflect solar energy away from Earth, resulting in more global warming [1]. Thus, future work requires the effects of pollution control on global warming.

There is uncertainty in the literature on the % of O₂ contributions by the ocean to the atmosphere and more precise data are required. Data on the relation between the RQ of biomasses and their variation with the increasing concentration of CO₂ are required. High RQ values for biomass are desired to provide more CO₂ sink by land and ocean biomass. But low RQ values are desired by the same biomasses to provide more O₂ production if O₂ concentrations need to remain at current level! The ideal scenario is to have a "phytoplankton forest" in the ocean along with seaweed. Botanists must explore the possibility of genetically modifying biomasses (e.g., PP in ocean and plants and trees on the land) and using artificial photosynthesis mimicking the natural photosynthesis for serving as a CO₂ sink and O₂ source to provide a high RQ and overcome the economic hurdles [91]. The effects of earth's mass loss due to mining of FF on earth's tilt angle must be investigated.

Are Keeling's data an ultimate judgement of what is happening with CO₂ sources and sinks, land and ocean biomasses, and ocean storage? Is Earth marching towards "death" without any respiration on the planet? Though it is suggested that the Earth has a life period of another 1700 years, extrapolating Keeling's data, more detailed modeling is

required to predict the decreasing oxygen concentration in the atm and the slow extinction of species on Earth.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/en17081800/s1>, The detailed step-by-step procedure for obtaining quantitative results is provided as supplemental materials titled “Supp Step by Step CO₂ budget Part II”.

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Data Availability Statement: Data are contained within the article and Supplementary materials.

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Nomenclature

AFFLUE	Annual Fossil and Land Use Energy
AI	Artificial Intelligence
ARQ	Apparent Respiration Quotient
BS	Biological system
$\dot{C}(s)$	Carbon release rate, GT/year
CCP	Coal Combustion Project
CE	Carbon Emission
CH	Carbohydrate
CS	Carbon storage
CO _{2eq}	CO ₂ equivalent
DAF	Dry ash free
\dot{E}_{FFLU}	Energy release rate from FFLU, Exa J/year
EF	Energy fraction
EPA	Environmental Protection Agency
EPICA	European Project for Ice Coring in Antarctica
Exa g	10 ¹⁸ g = 1000 Peta g or 1000 Giga tons or 1000 billion tons = 10 ⁶ Tera g = 10 ⁹ Giga g = 10 ¹² Mega g = 10 ¹⁵ kg
ExR	Exchange ratio = 1/RQ
F	Fat
F _i	constants used in many relations; Table 4 lists them.
FF	Fossil Fuel
FFLU	Fossil fuel and Land use
GCP	Global Carbon Project
GPP	Gross Primary Production
GWP	Global warming Potential-CO ₂ eq GWP100: GWP over 100 years
HBS	Hypothetical biological System
HH	Hypothetical Human
HHV _{O2}	Energy released per Peta Mol of O ₂ = 448 Exa J per Peta mol of O ₂
IPCC	Inter-government Panel on Climate Change
LBM	Land biomass
LOWBM	Combined land and ocean water biomasses

LU	Land use
M	Molecular weight
MOM	Marine organic matter
$\dot{N}_{CO_2}, \dot{N}_{O_2}$	Mole rates of CO ₂ , O ₂ per year
$\dot{N}_{CO_2, FFLU}, \dot{N}_{O_2, FFLU}$	CO ₂ release rate from FFLU and O ₂ consumption by FFLU, Peta moles/year
NBS	Non-biological systems
NEP	Net Ecosystem Production, NEP = NPP – Loss due to Dead Matter
NG	Natural gas
NH	Normal Human
NOAA	National Oceanic and Atmospheric Administration
NPP	Net Primary Product, NPP = GPP – Respiration Rate _–
OW	Ocean water
OWBM	Ocean water biomass
Per meg	1 molecule out of 1000,000 oxygen molecules, 1 ppm in air = 4.76 per meg
PP	Phytoplankton
ppb	parts per billion
ppm	parts per million or molecules per million molecules 1 ppm in atmosphere = 7.77 GT for CO ₂ , 2.12 GT for C, 1 ppm O ₂ in atmosphere = 5.65 GT
PQ	Photo-synthetic quotient, = 1/RQ
Quad BTU	10 ¹⁵ BTU
RQ	Respiratory quotient
RQ _{Glob}	Global RQ based on Keeling's data on CO ₂ and O ₂ , (d[CO ₂]/dt)/(d[O ₂]/dt)
RQ _{Glob(En)}	Energy based Global RQ = Ratio of moles of CO ₂ release and O ₂ consumption by FFLU
RR	Redfield ratio = 1/RQ
SDG	Sustainable development goal
SST	Sea surface temperature
UCF	Unit carbon formula
Y _k	mass fraction of element k, g of k/g of mixture
ZJ	Zetta joule, 10 ²¹ J
[k]	Species k in moles or ppm per unit volume

Appendix A. CO₂ Added to Atmosphere and O₂ Removed from Atmosphere in GT per Year

(a) CO₂ added to the atmosphere.

$$\left(\frac{\text{Net CO}_2 \text{ in Giga Tons, atm}}{\text{year}} \right) = \frac{d[\text{CO}_2]}{dt} \left(\frac{\text{ppm}}{\text{year}} \right) * 10^{-6} \frac{\text{Peta mole of CO}_2}{\text{Peta mole air}} * N_{\text{air}} (\text{Peta Mole}) * M_{\text{CO}_2} \left(\frac{\text{Giga Tons}}{\text{Peta Mole}} \right) \quad (\text{A1})$$

$$\left(\frac{\text{Net CO}_2 \text{ in Giga Tons, atm}}{\text{year}} \right) = 7.79 \frac{d[\text{CO}_2]}{dt} \left(\frac{\text{ppm added}}{\text{year}} \right) \quad (\text{A2})$$

where $N_{\text{air}} = 1.77 \times 10^5$ Peta moles. Generally for any trace GHG of molecular weight M_{GHG}

$$\left(\frac{\text{Net GHG in Giga Tons, atm}}{\text{year}} \right) = \frac{d[\text{GHG}]}{dt} \left(\frac{\text{ppm}}{\text{year}} \right) * 10^{-6} \frac{\text{Peta mole of GHG}}{\text{Peta mole air}} * N_{\text{air}} (\text{Peta Mole}) * M_{\text{GHG}} \left(\frac{\text{Giga Tons}}{\text{Peta Mole}} \right) \quad (\text{A3})$$

(b) O₂ Removed from Atmosphere

$$\left(\frac{\text{Net O}_2 \text{ in Giga Tons, atm}}{\text{year}} \right) = \frac{d[\text{O}_2]}{dt} \left(\frac{\text{ppm}}{\text{year}} \right) * 10^{-6} \frac{\text{Peta mole O}_2}{\text{Peta mols air}} * N_{\text{air}} * M_{\text{O}_2} * \left(\frac{\text{Giga Tons}}{\text{peta mole}} \right) \quad (\text{A4})$$

$$\left(\frac{\text{Net O}_2 \text{ sink in Giga Tons, atm}}{\text{year}} \right) = 5.66 \frac{d[\text{O}_2]}{dt} \left(\frac{\text{ppm}}{\text{year}} \right) \quad (\text{A5})$$

Appendix B. CO₂ and O₂ Balance Equations in Non-Dimensional Form and Solutions for O₂ Production by Land Ocean Biomasses and CO₂ Storage by Ocean

O₂ Balance: Dividing the oxygen conservation equation (Equation (6)) by O₂ moles consumed by FFLU (combined FF and land use energy), defined as

$$\frac{\left\{ \frac{d[O_2]}{dt} \right\}_{atm} * 10^{-6} * N_{air}}{\dot{N}_{O_2,FFLU}} = (1-x) \text{ or } \frac{\left\{ \frac{d[O_2]}{dt} \right\}_{atm} * F_{Bal}}{\dot{E}_{FFLU}} = (1-x) \quad (A6)$$

where x is defined as

$$x = \frac{\dot{N}_{O_2,LOWBIM}}{\dot{N}_{O_2,FFLU}} = \frac{HHV_{O_2} \dot{N}_{O_2,LOWBIM}}{\dot{E}_{FFLU}} \quad (A7)$$

where $F_{Bal} = 10^{-6} * N_{air} * HHV_{O_2} = 79.3$ (Table 4) with $N_{air} = 1.77 \times 10^5$ Peta moles, $HHV_{O_2} = 448$ Exa J/Peta mole O₂, and $\dot{N}_{O_2,FFLU} = \frac{\dot{E}_{FFLU}}{HHV_{O_2}}$ and \dot{E}_{FFLU} in Exa J/year. The left-hand side is known from the curve fit constants term in Keeling's data on O₂ [27] and, hence, "x" can be estimated from Equation (11).

The advantages of normalizing with $\dot{N}_{O_2,FFLU}$ are that (i) the denominator of O₂ sink by fossil fuels is known once the annual energy consumption is known and (ii) energy-based global $RQ_{Glob(En)}$ can be converted into GT/year by using CO₂ in GT/Exa J of energy release by FFLU = 0.1 * $RQ_{Glob(En)}$ (Equation (19))

If annual \dot{C} emission data by FFLU (GT/year) are reported instead of energy data, then $\dot{N}_{O_2,FFLU} = \frac{\dot{C}}{M_C * RQ_{FFLU}}$, Peta mole/year,

$$\frac{\left\{ \frac{d[O_2]}{dt} \right\}_{atm} * 10^{-6} * N_{air}}{\dot{N}_{O_2,FFLU}} = (1-x) \text{ or } \frac{\left\{ \frac{d[O_2]}{dt} \right\}_{atm} * RQ_{FFLU} * F_{CGt}}{\dot{C}_{FFLU}} = (1-x) \quad (A8)$$

where $F_C = M_C * 10^{-6} * N_{air} = 2.13$,

CO₂ Balance:

Dividing Equation (7) by O₂ moles consumed by FFLU ($\dot{N}_{O_2,FFLU}$) recalling that $\dot{N}_{CO_2,FFLU} = RQ_{FFLU} * \dot{N}_{O_2,FFLU}$ and simplifying,

$$\frac{\left\{ \frac{d[CO_2]}{dt} \right\}_{atm} * 10^{-06} * N_{air}}{\dot{N}_{O_2,FFLU}} = RQ_{FFLU} - RQ_{LOWBIM} * x - y \quad (A9)$$

where

$$y = \frac{\dot{N}_{CO_2,st,ocn}}{\dot{N}_{O_2,FFLU}} = RQ_{FFLU} \frac{\dot{N}_{CO_2,st,ocn}}{\dot{N}_{CO_2,FFLU}} \quad (A10)$$

Using x from Equation (A6), "y" is solved as

$$y = RQ_{FFLU} - RQ_{LOBM} * \left\{ 1 - \frac{\left\{ \frac{d[O_2]}{dt} \right\}_{atm} * F_{Bal}}{\dot{E}_{FFLU}} \right\} - \left\{ \frac{F_{Bal} * \left\{ \frac{d[CO_2]}{dt} \right\}_{atm}}{\dot{E}_{FFLU}} \right\} = RQ_{FFLU} - RQ_{LOBM} + \frac{\left\{ \frac{d[O_2]}{dt} \right\}_{atm} * F_{Bal} * \{RQ_{LOBM} - RQ_{Glob}\}}{\dot{E}_{FFLU}} \quad (A11)$$

CO₂ Budget

$$CO2_{Fr,atm} = \frac{\left\{ \frac{d[CO_2]}{dt} \right\}_{atm} * 10^{-6} * N_{air}}{\dot{N}_{O_2,FFLU} * RQ_{FFLU}} = \frac{\left\{ \frac{d[CO_2]}{dt} \right\}_{atm} * F_{Bal}}{\dot{E}_{FFLU} * RQ_{FFLU}} \quad (A12)$$

where $F_{Bal} = 79.3$. With definition of $RQ_{Glob(En)}$,

$$CO2_{Fr,atm} = \frac{\left\{ \frac{d[CO_2]}{dt} \right\}_{atm} * F_{Bal}}{\dot{E}_{FFLU} * RQ_{FFLU}} = \frac{RQ_{Glob(En)}}{RQ_{FFLU}} \quad (A13)$$

CO₂ Sink Rate Due to LBM and OWBM: Multiplying by “x” by z, the O₂ source due to ocean biomass, and by (1 – z), the O₂ source via land biomass are given as as follows:

$$\frac{\dot{N}_{O_2,OWBM}}{\dot{N}_{O_2,FFLU}} = z * x \quad (A14)$$

$$\frac{\dot{N}_{O_2,LBM}}{\dot{N}_{O_2,FFLU}} = (1 - z) * x, \quad (A15)$$

CO₂ Storage Rate in Ocean

$$CO2_{Fr,St,Ocn} = \frac{\dot{N}_{CO_2,St,Ocn}}{\dot{N}_{CO_2,FFLU}} = \frac{y}{RQ_{FFLU}} \quad (A16)$$

Combining with CO₂ sink by ocean biomass and using definition of $RQ_{Glob(En)}$

$$\frac{\dot{N}_{CO_2,St,OcnLOWBM}}{\dot{N}_{CO_2,FFLU}} = \frac{\dot{N}_{CO_2,St,Ocn} + \dot{N}_{CO_2,LOWBM}}{\dot{N}_{CO_2,FFLU}} = \frac{\dot{N}_{CO_2,FFLU} - \dot{N}_{CO_2,atm}}{\dot{N}_{CO_2,FFLU}} = 1 - \frac{RQ_{Glob,En}}{RQ_{FFLU}} \quad (A17)$$

Appendix C. Estimation of “Z” (O₂ Transferred from Ocean to Atm /Total O₂ Produced) from C Sink on Land and C Emission

When C emission data and C sink on land are available along with Keeling’s data on O₂ vs. year, the “z” may be estimated. The procedure is outlined below:

1. Estimate the rate of decrease in O₂ from the atmosphere from Keeling’s data.
2. Use left-hand side of Equation (A8) to determine “x” ratio of O₂ produced to O₂ used by FFs and LU.
3. Since the ratio of O₂ production by land to total O₂ production is (1 – z) * x and since O₂ production is for every mole of C(s) or CO₂ sink, then O₂ production via land in Peta mole/year = (1 – z) * x * (annual O₂ sink in Peta moles due to FFLU) = CO₂ or C(s) sink on land in Peta moles on land per year = C(s) sink on land (GT/year) * 10¹⁵ (g/GT) / {RQ_{BM} * M_C (g/mol) * 10¹⁵ (mole/Peta mole)} = C(s) sink on land (GT/year) / ({RQ_{BM} * M_C g/mol}).
4. A formula for z can be derived as follows:

$$(1 - z) * x = \frac{\{C \text{ sink on land}(GT/year)\} / RQ_{LBM}}{(O_2 \text{ sink in peta moles/year}) \text{ due to FFLU}} = \frac{\{C \text{ sink on land}(Gt/year) / RQ_{LBM}\}}{\{(C \text{ emission in GT/year}) \text{ due to FFLU} / RQ_{FFLU}\}} \quad (A18)$$

$$z = 1 - \frac{\{C \text{ sink onland}(GT/year) / RQ_{LBM}\}}{\{(C \text{ emission in GT/year}) \text{ due to FFLU} / RQ_{FFLU}\}} \quad (A19)$$

where O₂ sinks due to FFLU, Peta moles/year = (C emission in FFLU in (GT/year) / (RQ_{FFLU} * M_C), and M_C = 12.01.

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