

Global SOC, Annual NPP and CO₂ Turnover Time

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Abstract: This new study revised interlinked issues of global soil organic carbon (SOC), annual net primary productivity (NPP) and atmospheric CO₂ turnover time (τ). Soil is confirmed as both the greatest sink and source for excess atmospheric CO₂. Most terrestrial NPP (~218 Gt C/yr) is ultimately processed in topsoil and SOC stocks now total >10,000–12,000 Gt. More excess carbon is released into the air and water from SOC loss (>20 Gt C/yr) due to land clearance for pasture/crops, fires, agrichemical poisoning and erosion, than from fossil fuels (~10 Gt C/yr). NOAA's Barrow bounce and isotopic analyses support high terrestrial flux up to ~800 Gt C/yr and CO₂ turnover time of ~1–4 years. Earth's re-humification via compost offers the best and only practical/time-critical fix for climate, strategy for species extinction plus remedy for human health.

Keywords: topography; soil carbon sequestration; humus; earthworms; climate, vermi-compost.

1. Introduction

A 10-yr case study by the author (Blakemore [2018b](#) *Soil Sys.* 2, 64)[1] presented a reasoned argument that undulating and rugose terrain was being neglected in most accounts of natural resources. When considered, fractal land-surface area at least doubles, from prior flat 15 Gha to >30 Gha with three major, ecologically interlinked, consequences: 1/. Soil organic carbon (SOC) raised from 1,500–3,000 to >8,580 Gt; 2/. Global biomass and biodiversity at least doubled (Blakemore [2018b](#): figs. 11–15, tab. 10)[1]; and 3/. Net primary production (NPP) grew from ~60 to ~218 Gt C/yr. Latest atmospheric isotope research implicitly supports these land recalibration results.

Three likely errors in the original paper require clarification as does status of prior SOC stocks, for example, prior SOC total by Reiners (1973)[2] was 9,120; IPCC (2013)[3] had up to 4,800; Lal et al. ([2011](#): 1)[4] 4,600 (plus 1,700 inorganic carbon); Köchy et al. (2015)[5] 3,000; and "HWSO" dataset 2,469.5 Gt to 1 m (Heiderer & Köchy [2011](#): 50, tabs. 11,18)[6] that doubled for >1 m is >4,938 Gt. Determining a true SOC value is imperative for estimating scope of annual global carbon cycles.

2. Subsequent Studies Supporting SOC Stock Raise

Overall, the original study (Blakemore [2018b](#): tab. 5)[1] found flat soil surfaces are about doubled for measurements down to sample size of cm², or quadrupled at mm² scale. Greater soil area accommodates more plants/biocrust/phytomenon and has more exposure to the elements thereby validating productivity (NPP) and soil organic matter (SOC) increases. Grounded studies subsequent to the 2018 terrain/topsoil recalibration paper tend to confirm new concepts and support elevated results, in particular SOC stocks reasonably raised above 8,580 Gt to >10,000–12,000 Gt partly due to starting values now much higher than just 1,500–3,000 Gt SOC, e.g.:

1. IPCC's most recent report (IPCC [2019a](#): 2-97)[7] has: "global soil organic carbon (SOC) stock down to 1 m depth, varying between 2500 Pg to 3400 Pg with differences among databases largely

attributable to C stored in permafrost". Median SOC value of ~3,000 Gt doubled >1 m is ~6,000 and, if reasonably doubled again for neglected terrain, is ~12,000 Gt.

2. IPCC (2019a, 2019b)[7–8] values consolidated with cryosols (permafrost) and peats are 4,700–5,600 Gt (median ~5,000) to >3 m, readily doubled for terrain to ~10,000 Gt SOC.
3. Tifafi et al. (2018)[9] found datasets, e.g. SoilGrids's 3,421 Gt, underestimate field data by >40% to likely give >5,700 Gt SOC to just 1 m soil depth (doubled for depth = ~11,400 Gt?).
4. Gross & Harrison (2019)[10] cite bulk density (BD) errors in SOC field data up to -36%.
5. Cotching (2018)[11] confirmed national SOC databases (e.g. Australia or UK) to limited depths underestimate on-the-ground field survey results by 8–83%.
6. Nichols & Peteet (2019)[12] report an overlooked 510 Gt extra SOC in northern peatlands.
7. Blakemore (2019a, 2019b, 2020)[13–15] collates how bulk density, flat-Earth, shallow soil and peat miscalculations now raise SOC totals from low earlier figures to >10,000 Gt.
8. Crowther et al (2019: fig. 2C)[16] falsely claims just 1,500 Gt SOC (from 4p1000.org?), but their SoilGrids dataset graph has 4,595 Gt to 2 m (pers. obs.) that may be doubled for terrain and soil deeper than 2 m plus an extra 510 Gt peat to >10,000 Gt SOC (Figure 1).

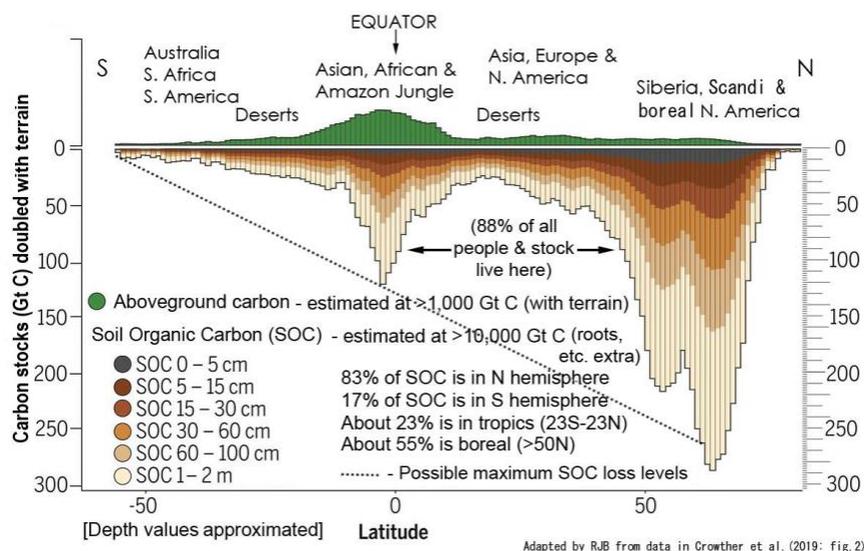


Figure 1. Adapted from Crowther et al. (2019: fig. 2C)[16] clearly demonstrating relative importance and geographical allocations of flammable trees and other aboveground vegetation vs. soil SOC carbon storage to just 2 m (yet base of boreal permafrost may reach 1.5 km). Forests are cleared and land degraded mainly to satisfy excessive red-meat diets[13,15]. Options for re-greening of dishes and of deserts, especially in over-grazed Australia, India, N. Africa and Mid East, offer greatest global potential for restoration of lost humus. Cf. Blakemore (2018: figs. 11–12, tab. 10)[1].

3. Corrections and Clarification

Three possible errors (and contingency Table 6) in the original Blakemore (2018b)[1] paper regarding SOC underestimation, soil Bulk Density (BD) backcheck and Net Primary Production (NPP) were clarified and corrected by Blakemore (2019a, 2019b, 2020)[13–15]. In summary:

1. SOC total is now at least >10,000–12,000 Gt (as noted above) (not just >8,580 Gt).
2. BD recalculations (Blakemore 2019a)[13] require just $\times 2$ –5 land area (not $\times 4$ –6).
3. NPP is confirmed within bounds of 120–220 Gt C/yr (~218?), GPP of $\gg 240$ Gt C/yr with soil respiration/decomposition (SR) ~200 Gt C/yr (Blakemore 2020)[15] (Table 1).

Table 1. Land productivity vs. human emission (assumed as fossil fuels FF but also due to SOC loss) showing soil humus is both Earth's greatest emission source and natural carbon capture store (CCS).

Reference ^A /Parameter ^B	NASA (2011)[17]	IPCC (2001: 188, 191; 2013: fig. 6.1, 547; 2019a, 2019b)[3,7–8,18]	Le Quéré et al. (2018: fig. 2)[19]	Blakemore (2018b: tab. 11, 2019a, 2019b, 2020)[1,13,15]
Terrestrial GPP (Gt C/yr) ^C	123	~123	123.2	>>240 (240–440)
Terrestrial NPP (Gt C/yr) ^C	63	~60	?	120–220 (~218?)
Total Soil Respiration (SR) ^C incl. Roots – Gt C/yr (%)	60 (87%)	40–70 (82–88%)	?	120–200 (90–95%) ^C
Terrestrial NEP = (NPP-SR)	3	5–10	?	10–20
FF emissions – Gt C/yr (%)	9 (13%)	~9 (12–18%)	10.9	~10 (5–10%)
Air (CO ₂) excess – Gt C/yr	+4	+4	+4.7	~4.7 (2.2 ppm)
Soil SOC stock (Gt C) ^D	2300	~4700–5600 ^D	3200–4100	>10,000 ^D

^A NASA, IPCC and Le Quéré et al. all also have a passive, mostly self-cancelling ocean/air exchange of ~80–90 Gt C/yr from surface ocean dissolved organic carbon DOC stock of 700–1000 Gt C (all the rest is DIC), here discounted as a relatively small net effect (ca. -0.4–2.4 Gt C/yr – see Le Quéré et al.[19] cf. Lee et al. 1998[20]). Plant respiration from leaves simultaneously cancels about a third of GPP, root respiration is ~30% of total soil respiration. NASA has ~50:50 allocation above- or below-ground yet fewer than 10% of studies measure belowground NPP[15]. Unrealistic artificial CCS of fossil fuel gas is, at best, 0.7 Gt or just 0.3% vs. ~218 Gt C/yr “natural” NPP, most ultimately stored, respired or combusted. Halting all fossil use would have zero effect on excess CO₂ drawdown that is only possible with topsoiling/rehumification via earthworm-worked compost. [Le Quéré et al. (2018)[19] data now replaced by www.earth-syst-sci-data.net/11/1783/2019/ without much change].

^B In general, despite minor isotopic bias (plants preferentially use standard ¹²C over minor ¹³C or trace ¹⁴C), there is no CO₂ source discrimination for photosynthesis regardless if “natural” or human induced/FF.

^C NPP = GPP-PR; IPCC (2019a: 2-94)[7] say plant autotrophic respiration (PR) is “approximately one half of GPP”; SR & RR after Riach et al. (2002)[21], Bond & Thompson (2010)[22], etc. (see Blakemore 2019a, 2020)[13,15].

^D IPCC [7–8] SOC values vary yet miss crucial new data from Blakemore (2018)[1] and as proffered herein.

Original and latest isotope studies using ¹³C/¹²C, ¹⁸O/¹⁶O or ¹⁸OCO, and ¹⁷O/¹⁶O support raising GPP/NPP (e.g. Welp, Keeling et al. (2011)[23], van der Velde et al. (2013)[24], Liang et al. (2017)[25] and Laskar et al. (2019)[26]). With a passive, self-cancelling ocean exchange at ±80–90 Gt C/yr, isotope estimates give global carbon exchange scaled up to 772, 779.2 or as high as 897 Gt C/yr. Koren et al. (2019: figs. 1, 4b)[27] model NPP of 114 Gt C/yr and air↔leaf flux of -400–750 Gt C (i.e., ±350 Gt C/yr). Human fossil fuel (FF) emissions of +10 Gt C/yr mainly in northern hemisphere are trivial against such large leaf fluxes exemplified by Scripps' Keeling curves “natural” net CO₂ fluxes of ±20 Gt C/yr at Mauna Loa, Hawaii and ±40 Gt C/yr at NOAA's Barrow, Alaska (Figure 2).

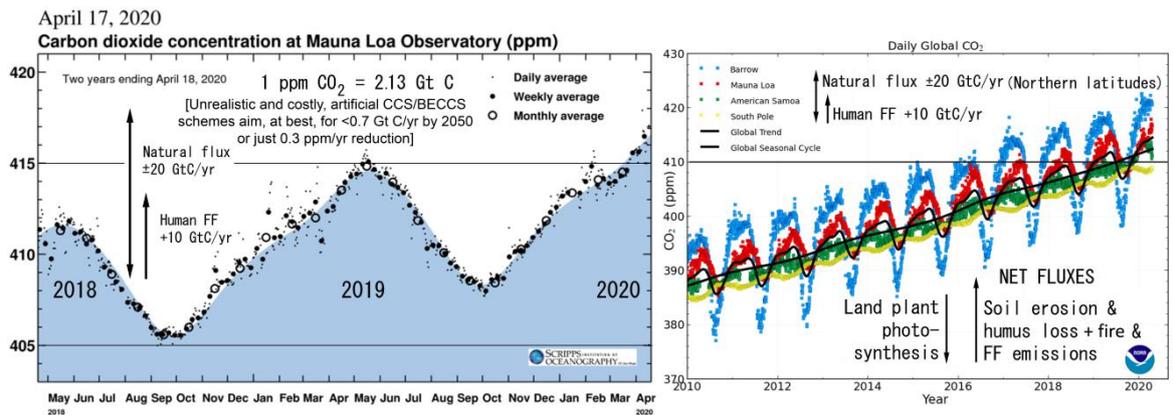


Figure 2. Human activities disrupt plant/soil fluxes more than fossil fuel (FF) burning does: Mauna Loa's flux of +10ppm or >20 Gt C just for winter months is greater than annual FF +10 Gt C/yr that, if it were sole influence, would raise rates by 4.7 ppm rather than current 2.2 ppm. Natural rhythm in Barrow's short summer drawdown flux (above rhs in blue of ~20 ppm = NPP >40 Gt C) is in boreal region with just ~15% of total vegetation (Fig. 1). At twice Mauna Loa's flux (~10 ppm), full-yearly global NPP is seemingly within 200–400 Gt C/yr. Despite corona virus industrial shutdowns, 2020's peak spiked to 420 ppm showing FF CO₂ reduction has disproportionately lesser effect on carbon totals that are more dependent upon relentless soil SOC loss. Fewer cars or less red meat help cut GHG emissions, but drawdown is possible only with organic humus restoration. (Temperatures may yet rise due to lower aerosol radiative forcing of smog plus its cloud seeding).

Welp, Keeling et al. (2011)[23] stated: "Our analysis suggests that current estimates of global gross primary production, of 120 petagrams of carbon per year, may be too low, and that a best guess of 150–175 petagrams of carbon per year better reflects the observed rapid cycling of CO₂." As global carbon cycle is almost entirely due to land's GPP and the ocean's GPP is negligible, assuming NPP is about half of GPP gives their global land NPP of 75–88 Gt C/yr. However, Liang et al. (2017)[25] used oxygen isotopes to model GPP and found: "The **terrestrial flux** is quantified to be $345 \pm 70 \text{ PgC year}^{-1}$, falling in the range reported in the literature, $200\text{--}660 \text{ PgC year}^{-1}$ and CO₂ turnover time " τ is $1.9 \pm 0.3 \text{ years}$." This potentially gives a land NPP of ~172.5 Gt C/yr (not just 60 Gt C/yr).

IPCC (2001: 191)[18] had "leaf water" carbon flux of 270 Gt C/yr giving a ~3 yr atmospheric CO₂ transit time. Liang et al. (2017)[25] derived an estimate of $130 \pm 25 \text{ Gt C/yr}$ for GPP with a "best guess" for "soil invasion" of $120 \pm 20 \text{ Gt C/yr}$, but they speculated (fig. 5D) GPP up to 220 Gt C/yr. Of note is that prior or subsequent [26] isotope studies had much higher terrestrial flux, up to 722 or 817 Gt C/yr, values more than twice Liang et al.'s 345 Gt carbon flux figure, suggesting their GPP guestimates may be doubled too: From 130–220 up to 260–440 Gt C/yr. This agrees with upping of NPP to 120–220 (viz. ~218 Gt C/yr) and also with observed soil respiration/decomposition rate of $\sim 100 \pm 12 \text{ Gt C/yr}$ [22] also doubled for terrain to ~200 Gt C/yr (as detailed in Blakemore 2020)[15].

Assuming ~50% of GPP carbon is released by Plant Respiration (PR)[7,17] and reasoning a land NPP of ~218 Gt, if matched by PR of ~200 Gt, gives GPP (= NPP + PR) of ~418 Gt C/yr, well within the realm of 395–817 Gt C/yr terrestrial flux (Laskar et al. 2019)[26] and allowing ample allocation of up to ~400 Gt C/yr for combined non-photosynthetic "leaf water" and passive CO₂ "soil invasion".

The most feasible explanation for increased GPP and flux rates (assuming LAI leaf-area-indices are accurate) is land area raised as per Blakemore (2018b)[1]. Factoring in terrain best justifies newly modeled values. Furthermore, the ocean is a closed-system passively absorbing as little as 0.4 Gt

C/yr from excess atmospheric CO₂ (Lee et al. 1998)[20], or just 4% of the 10 Gt C/yr emitted by fossil fuels, thus it is not a main consideration of this report, neither should it be for IPCC nor for other carbon-cycle models. Land/soil:sea:fossil flux partition ratios are reported as 817:80:10 Gt C/yr [26].

In graphical summary, data in IPCC (WG1-TAR1 2001: fig. 3.1d)[18] as presented by Houghton (2007: fig. 1)[28] and forming a basis for IPCC (2019a,b) [7–8] are tentatively revised (Figure 3).

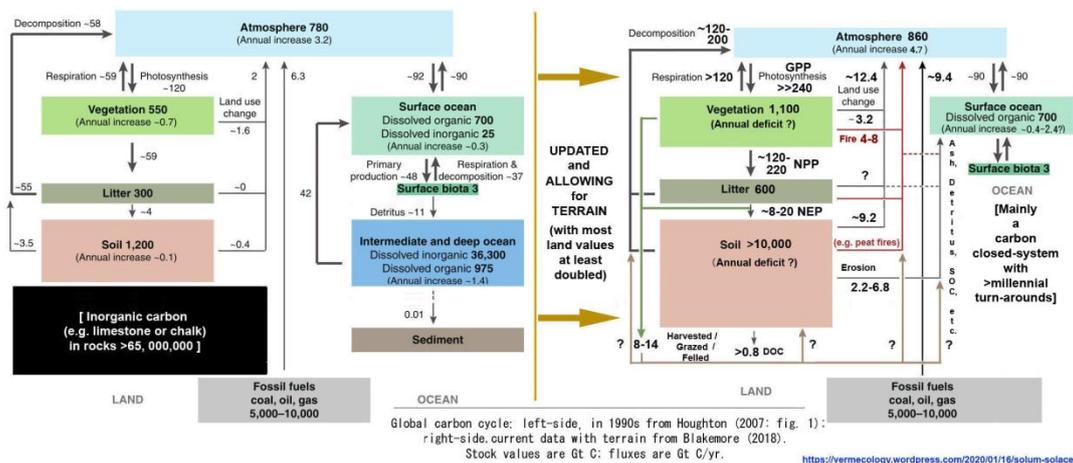


Figure 3. Carbon cycle relevant to atmospheric CO₂ accumulation and land sequestration fixes (after Houghton 2007: fig. 1)[28] updating IPCC, NASA/NOAA data with details provided in Blakemore (2020)[15]. Ocean loading from topsoil erosion, wash-off, drainage and ash far exceeds atmospheric input. Dissolved soil organic/inorganic C (DOC/DIC) also leaches into groundwater or flows to seas.

4. Corroboration and Consequences

As a general rule, carbon turnover time (τ) is a carbon stock reservoir divided by its flux (either GPP or just NPP). Rapid replacement of all 860 Gt C in atmospheric CO₂ is realistic if land's active GPP is ~200–800 Gt C/yr ($\tau = 860 / \text{GPP} = \sim 1\text{--}4$ yrs) with a lesser, passive exchange of net ~0.4–2.4 Gt C/yr into CO₂ + HCO₃ saturated seas. As NPP is about half GPP, an NPP of ~220 has $\tau = \sim 2$ yrs.

Independent agreement for terrestrial NPP of ~218 Gt C/yr, or above, with potential NEP of 10 Gt C/yr $\times 2$ for terrain, and CO₂ turnover time of 1–4 yrs are from diverse studies, e.g.:

1. NOAA's Barrow site net summer drawdown if ~20 Gt C/yr (Fig. 3), from Taiga/Tundra being just ~9% of annual global NPP (Blakemore 2018a: fig. 3)[1], gives terrestrial NPP ~220 Gt C/yr [Q.E.D.]. This is mainly from steppes, nil for seas (Bartsev et al. 2012: fig. 3)[29]. Citing NOAA (www.esrl.noaa.gov/gmd/ccgg/isotopes/c13tellsus.html): "Oceanic exchange—which would affect total carbon dioxide but not $\delta^{13}\text{C}$ —appears to play little to no role in determining overall CO₂ at Barrow."
2. Revisiting Darwin's work a Century later, Lee (1985: tabs. 18, 21)[30] has mean earthworm surface casts dry mass of 105 t/ha/yr and about equal subsoil casting gives 210 t/ha/yr. With a 26 Gha topsoil mantle this is 5,460 Gt/yr humus processing. At an average cast carbon content of ~4% gives 218.4 Gt C/yr or about the entire annual NPP, as to be expected for balanced Nature.
3. Duursma & Boisson (1994: 124, 134–5)[31] for oceans state: "The turnover time of water masses, which transport CO₂ into the deep sea in polar regions, where the CO₂ is released at lower latitudes, is of the order of a thousand years (650 year in the Atlantic to 2000 in the Pacific)... Increased atmospheric CO₂ will only slightly affect the CO₂ level in the oceans, since the latter contain 55 times more CO₂ than the

atmosphere. Thus there will be no feedback based on increased atmospheric CO₂, or at most very little (<2 % of effects on land)... The average annual primary production of the world oceans of 30 gigatons carbon".

4. UNEP (2002: 10)[32] had 320 Gt C/yr GPP = NPP of 160 (-30 in sea =>130 Gt C/yr on flat land?).
5. Dusenage et al. (2018: fig. 1)[33] ignore ocean's minor contribution, stressing the value of land.
6. Terrestrial NEP (IPCC 2001, Liang et al. 2017)[18,25] of 10 Gt C/yr × 2 for terrain = 20 Gt.
7. Prof. Rattan Lal [34–36] endorses SOC and NPP rate re-evaluations from [1] as reasonable.
8. For atmospheric ¹²C¹⁶O₂, IPCC (2007: 948)[37] says: "turnover time is only about four years", Berry (2019)[38] has "4 to 5 years" (cf. with different reckoning Blakemore (2019c)[39] has "<3.6 yrs" for NPP or ~1.8 yrs for GPP). Using other C and O isotopes Welp, Keeling et al. (2011)[23], Liang et al. (2017)[25] and Laskar et al. (2019)[26] gave global CO₂ turnover times of 0.9–2.8 yrs (median ~1.8 yrs) , mainly due to terrestrial terrain.

In addition to carbon SOC pool, other factors affecting storage rates in soil are, for example: Leaf litter/log necromass, roots, earthworm biogenic calcite in 'inorganic' carbon (SIC) and earthworm bodies washing off into rivers (Blakemore 2019d)[40], plus dissolved organic/inorganic carbon (DOC/DIC) leaching. Total SOC from values herein of up to 12,000 Gt, may be increased 27% for glomalin [41] to 15,000 Gt with an additional >1,000 Gt in plant root/mycorrhiza and 600 Gt in surface litter/logs (Figs. 1,4) to likely sum >16,600 Gt C. Plus a partly biogenic inorganic SIC pool of >1,558 to 2 m (Lal 2019a: tab. 1)[33] with a dissolved inorganic DIC pool of 1,404 (= 2,962 Gt C), doubled for depth/terrain to ~6,000 Gt, yields >22,600 Gt soil carbon *in toto*.

5. Conclusions

Whittaker & Likens (1973)[42] said: "Despite the immensity of the biosphere, man has reduced its biomass and is beginning, with pollution, to affect its productivity." As natural and GPP carbon cycling (400–800 Gt C/yr) is up to 80 times fossil fuel emissions (~10 Gt C/yr), the cause of CO₂ accumulation in air is inability of biomes to fix and reabsorb excess due to biomass clearing, grazing, poisoning, burning and an unwitting destruction of topsoil with critical decline of earthworms [38,42]. Referring to taiga and the steppes (from whence the author has recently described new earthworm species [44]), Bartsev et al. (2012: fig. 3)[29] also noted: "measures taken by the world community to reduce greenhouse gas emissions are of less importance than preservation of wild natural resources." The latest, 1,542 page, IPCC (2019a)[7] land report (not marine) mentions "compost" just 14 times, "earthworm" once (both inappropriately linked to "biochar" that offers no advantage over time-proven compost and may actually harm soils' essential functions and beneficial fauna), and hits for "humus" are zero but "fish" get >100! Yet immediate application of natural, organic vermi-compost helps restore humic SOC and S/ECCS [39,43] offering a scalable, mostly cost-free and completely safe remedy to time-critical global species extinctions caused by interlinked and cumulative factors of agricultural poisons plus topsoil erosion that are exacerbated by climate [38].

The *Drawdown Review* (2020: 13)[45] supports soil as the only feasible way to remove excess CO₂ from air (98.5%), compared to costly, overhyped and un-natural CCS (1.1%) or ocean (0.4%).

Regarding new NPP/GPP estimates herein, how reliable is the current 'official' data? Before remarking on the uncertainties and complexities of previous ¹⁸O¹⁶O isotope standard estimates, Beer et al. (2010)[46] said: "In the absence of direct observations, a combined GPP of all terrestrial ecosystems of 120 Pg C year⁻¹ was obtained by doubling global biomass production estimates without an

empirical basis of spatially resolved biomass production and its relationship to GPP." In other words, it was a best guess. Their source was IPCC TAR-3 report (2001: tab. 3.2)[18] with NPP of ~60 Gt C/yr, but from a 'flat-Earth' of just ~15 Gha. When doubled for terrain to ~30 Gha this NPP becomes ~120 Gt C/yr, but may be increased further to account for often neglected sub-soil NPP, root exudates, etc.

Whilst isotopic analyses by Welp, Keeling et al. (2011: supplement)[23] led to a "best guess for terrestrial GPP" as high as 175 Gt C/yr, their soil invasion estimate within an uncertainty of 15–450 Gt C/yr had a likely range of "50–220 Pg C yr⁻¹ .. a relatively high case, for which there is little evidence at the moment, and lower values would increase GPP". Moreover, they provided a global turnover time (τ) as short as just 0.9 yrs requiring ~900 Gt C/yr flux to recycle all atmospheric CO₂ carbon each year

Terrain allowance thus raises all land values and best explains annual global carbon flux from isotopic analyses, as noted above, of up to 722–817 or as high as 900 Gt C/yr. An NPP value of ~218 Gt C/yr (Blakemore 2018b)[1] may therefore be entirely reasonable and is substantiated by Barrow drawdown data. Furthermore, a justifiable GPP of ~436 Gt C/yr gives a ~2 year CO₂ turnover time.

Certainties are that CO₂ is rising, land is not flat and ignorance of soil outweighs knowledge. Figures in this report are not definitive although more realistic than those by proponents of just 60 Gt C/yr NPP, 15 Gha terrain, or 1500 Gt SOC who must now raise their manifestly low values.

Conflicts of Interest: The author freely declares no external funding nor conflict of interest.

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