

1 Article

2 Non-flat Earth Recalibrated for Terrain and Rugged Soil Relief

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8 **Abstract:** Earth's land surface area is raised from conventionally flat 15 to 64 Gha to account for hilly
9 undulation and soil relief detail. Three main aspects are: topography, rugosity/tortuosity and micro-
10 relief/porosity of vegetation-free ground. Recalibration is arrived at from four approaches: first,
11 direct empirical estimates from the few compiled satellite or LiDAR data with means of +2.5–26%
12 progressively overlain by +94% at cm² scale for soil ruggedness then +108% for mm² micro-relief;
13 second, from digital elevation models with 1.6–2.0 times flat areas; third, by 'reverse engineering'
14 global soil bulk densities and carbon reserves requiring $\times 2$ –6 land. Finally, a Fermi estimation
15 conveniently sets the World's new surface area – that exposed to Sun, air and rain – at 100 Gha (with
16 36 Gha flat ocean). Soil organic carbon (SOC) is thence raised to 8,580 Gt mainly in SOM/humus
17 with its biotic complexity plus roots, VAM-fungi and leaf-litter, that itself = 17,800 Gt. Although four
18 to six times IPCC's or NASA/NOAA's calculations of just 1,500–2,300 Gt SOC, this is likely an
19 underestimation. Global biomass and biodiversity are at least doubled ($\times 2$ –3.5) and net primary
20 productivity (NPP) similarly increased on land to >270 Gt C yr⁻¹ due to terrain.

21 **Keywords:** Topographical land surface-area, soil carbon sequestration, climate, earthworms.
22

23 1. Introduction

24 This paper attempts to answer the simple question: 'What is the Earth's true surface area?'.
25 Surprisingly, this has no exact answer yet is key for determining the extent of the living world and
26 crucial for understanding our planet's essential life-support systems, especially the neglected soil.
27 Even the most basic information on soils – upon which we live and depend for 99% human food
28 (FAO-AGL 2004, Blakemore 2012, Pimental & Burgess 2013), 100% timber and natural fibres, to filter
29 all our drinking water, for medicines such as Penicillins, Streptomycins, Malacidins and now
30 Teixobactin or drugs like Ivermectin (anti-parasitic) and Bleomycin (anti-cancer), and which support
31 >98% of biota (Duursma & Boisson 1994, Fierer *et al.* 2007, Kallmeyer *et al.* 2012 and herein) whilst
32 also buffering pollution and climate change – is poorly known. For example: How much topsoil is
33 there? What is its rate of production and loss? How about total soil biodiversity, primary productivity
34 and the principal vulnerabilities or extinction threats? Part of the reason for knowledge deficit is lack
35 of a single "Soil Ecology Institute" comparable to myriad Marine, Atmospheric, Aquatic and
36 Astronomical research facilities around the globe (plus innumerable agriculture, chemistry,
37 microbiology or physics laboratories, albeit some claim a soil remit). A major oversight is ignoring
38 terrain, the main issue the current work confronts, as summarized in this image (Figure 1):-



(a) Stylized Landscape



(b) NASA/NOAA's Unrealistic Model View of the Same

39

40 **Figure 1.** (a) Hiroshige Utagawa's 1833 ukiyo-e print: "Bandits' Paradise: Hakone on the Tokaido" (looking towards Mt Fuji); it intuitively and stylistically demonstrates undulations with a patchwork mosaic of landforms and also shows how people closely follow each other, rarely looking out beyond the pack for tribal reasons of safety; (b) NASA/NOAA's alternate "flat-Earth" view of this landscape; remarkably, most current totals of biodiversity, productivity, plus carbon and other nutrient budgets based upon this model are consequently incorrect, widely underestimating true values.

46 *1.1. Land's surface area*

47 The present study builds on earlier work by the author (e.g. Blakemore 2012, 2016c, 2017a, b) and sources cited therein. Before focusing on topsoils/earthworms it is necessary to first consider a broader picture and the implications of increasing land relief. By long-standing convention, land area is measured on a common surface plane projected onto the ground, *i.e.*, as a two dimensional (2-D) flat planimetric area. NASA/NOAA estimates are of around 14.8–15.1 Gha land (29.2%) and 36.2 Gha ocean (70.8%) giving about 51 Gha for Earth's (flat) surface (www.ngdc.noaa.gov/mgg/global/etopo1_ocean_volumes.html). However, these totals consider neither terrain, topographical relief nor true undulating surface area. In other words, they ignore that land is naturally hilly and the soil bumpy. The reasoning from these Space, Oceanic & Atmosphere agencies (everything but Soil?) is along the lines that the Globe is so large that slight elevations such as the Alps, Andes, Antarctic Ranges, Atlas, Australia's Great Dividing Range, Ethiopian Highlands, Himalayas, Japanese Alps and the US's Rockies are insignificant. That may be essentially true at scales of observation around 10,000 km to 10,000 m at which Ying *et al.* (2014) also found topography negligible. Under-appreciated is that while the sea is horizontally flat, land invariably undulates and since it indeed occupies only 29% of the projected surface then the more planar versus hilly parts of just this proportion are inter-comparable. Conventionally, Earth's flat surface is as per the following table (Table 1).

64

Table 1. Earth's inadequate *status quo* flat land surface area model presently applied.

Flat areas	CIA 2008 (Gha)	FAO (Gha)*	%
Six Continents	13.36	13.01	87.0
Antarctica	1.40 (2% ice-free)	1.40	9.4
Greenland	0.22 (21% ice-free)	0.18	1.2
Rivers/lakes	-	0.15–0.37	1.1–2.5
TOTAL	14.98	~14.96	100

65
66

*FAO data from Nunn & Puga (2008: appendix) has ~15 Gha planimetric land including hot or cold deserts and water bodies (temporary freshwater inundations, paddy, bogs, marshes, or swamps may

67 yet be classed as having wetland soils), with roughly 80% or 12 Gha supporting terrestrial soils that
 68 provide various levels of organic carbon, natural fertility and species richness.

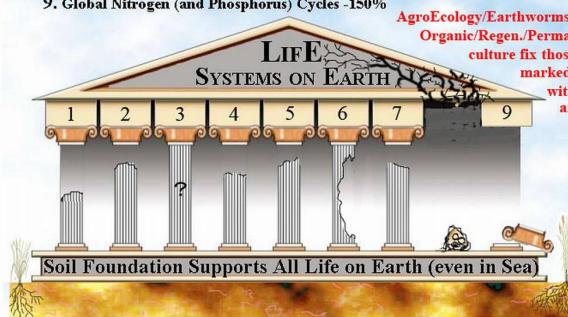
69 While flat planimetric areas are suitable for administration, they are inapplicable for ecology.
 70 Under that worldview, the land seems relatively unimportant compared to oceans and the current
 71 disparity for soil ecology is such that the World Scientists' Warning to Humanity (Ripple *et al.* 2017)
 72 originally from the majority of science Nobel laureates, notes that: "*the loss of soil productivity was listed*
 73 *as a concern in the 1992 scientists' warning, but this variable was not analyzed here due to a lack of global data*
 74 *on changes in soil productivity*". Their issues were "*not in order of importance or urgency*". Similarly, the
 75 UN's 17 Sustainable Development Goals (from their 2015 "2030 Agenda" [available online](#)) overlook
 76 soil as a major consideration, citing "soil" but twice under "*Goal 15: Life on Land*".

77 *1.2. Global Triage*

78 Applied Ecology (a type of triage but for which there is no Nobel Prize) is needed to resolve such
 79 essential issues and to provide clear direction for effective treatments. Triage cares not about past
 80 happenings nor distant possibilities, just the most immediate concerns. A recent review of planetary
 81 support systems provided by Rockström *et al.* (2009) may be taken as an initial step. Whilst ocean
 82 acidity was catalogued, the more rapid and urgent soil acidification (up to six times more severe than
 83 in the sea, see Blakemore, 2018a) was ignored as were topsoil erosion and salinity/sodicity issues.
 84 Overlooked too was soil microplastic pollution estimated at four to 23 times higher than the much
 85 publicized marine problem (Machado *et al.* 2018). Moreover, Rockström *et al.* and others were
 86 criticized for failing to adequately evaluate soils as summarized by Koch *et al.* (2016: 3-4): "*Discussions*
 87 *around biodiversity loss seldom refer to soil even though soil contains the most diverse and complex ecosystems*
 88 *on the planet. Soils contain over 98 per cent of the genetic diversity in terrestrial ecosystems* (Fierer *et al.*, 2007)
 89 *however soil biodiversity is not addressed in the Global Biodiversity Outlook (GBO-3) from the UN Convention*
 90 *on Biological Diversity (Secretariat of the CBD, 2010), and is not referred to in the popular International Union*
 91 *for Conservation of Nature (IUCN) Red List of Threatened Species (IUCN, 2012). Recent attempts to develop*
 92 *a global framework for assessing planetary resources also fail to recognize the vital role of soil in the biosphere...*
 93 *(Rockstrom *et al.*, 2009). This important work is influential in current reviews of sustainable development, but*
 94 *does not address soil as a critical contributor to buffering the thresholds of those boundaries.*" Rather, the
 95 current report determines that soil provides a foundation for all pillars of support for 'Life Systems
 96 on Earth', including those in the sea (Figure 2).

Rockstrom *et al.* (2009) Nine Planetary Pillars *

*1. Climate Change -60% 2. Ozone -20% 3. Aerosols ?
 *4. Ocean acidity -30% *5. Freshwater -20% *6. Chemicals **
 *7. Land Use (Agriculture) -25% 8. Biodiversity Loss -1000%
 *9. Global Nitrogen (and Phosphorus) Cycles -150%



98 **Figure 2.** Graphical triage summary of Rockström *et al.* (2009) and Diamond *et al.* (2015); although
99 interlinked, climate change is not the most urgent nor most pressing of environmental problems.

100 Two millennia ago Aristotle concurred with Plato in recognizing that soil erosion with loss of
101 humus and earthworms due to soil erosion around Athens from clearance of forest and overgrazing
102 was catastrophic to civilization (Montgomery 2008: 51). Still highly pertinent today as certainly the
103 most urgent of all the social, economic and ecological problems is the loss of our precious topsoil.
104 This is estimated, based upon UN's FAO data and that of Pimental & Burgess (2013), to occur at a
105 rate of 75 billion tonnes lost per annum, or 2,000 tonnes per second worldwide (Blakemore 2017a).
106 For vital soil organic carbon alone, Duursma & Boisson (1994: fig. 14) tallied 400–500 million tonnes
107 run-off via rivers to the ocean per year (= ~1 Gt humic SOM lost at 30 t per second). Combining these
108 two data confirm a reasonable SOM content of eroded topsoil as 1.3% (1 Gt SOM in 75 Gt topsoil on
109 a dry weight basis) as will be discussed later.

110 Moreover, erosion of agricultural soil is orders of magnitude greater than natural soils (hence
111 rivers are brown and silted and the air dusty in farming regions) and some farms may have just 12
112 year's soil remaining (Blakemore 2017a). For broadacre farmlands the situation is so dire that UN's
113 FAO predicts only another 50 years of harvests (Arsenault, 2014); similarly in China (Jie 2010) or UK
114 (Withnall 2014), is particularly bad in India and is seemingly catastrophic in Africa or the Americas
115 (Pimental & Burgess 2013, Blakemore 2018). Pimental & Burgess (2013) further report that 80% of the
116 world's agricultural land suffers moderate to severe erosion and, in the last 40 or so years, about 30%
117 of farmland was abandoned after becoming unproductive. Erosion rates, if from 'flat-Earth' models,
118 will also require elevating for terrain and relief.

119 1.3 Vital Global Resources

120 Basic requirements for continued humanity or other higher life are: oxygen in scale of
121 seconds, freshwater every few hours, and a daily need for food, along with habitat or shelter
122 with ecological infrastructure support. Smaller organisms, juveniles or invertebrates need
123 supplies almost constantly. Often the most limiting of factors relate to primary productivity as
124 tallied in this table (Table 2).

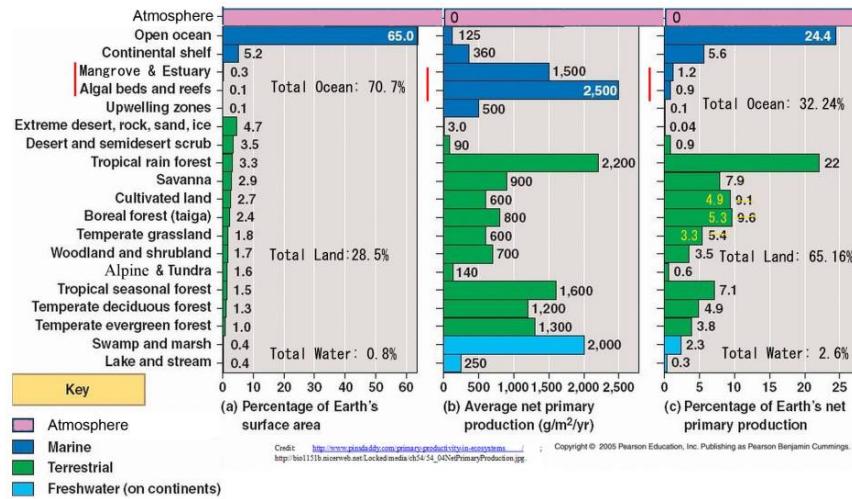
125 **Table 2.** Primary Productivity (P.P.) in terms of organic C and O₂ (Duursma & Boisson 1994: tab. 2).

P.P.	Area Gha	Org-C g/m ² /yr	Total Org-C Gt/yr	O ₂ g/m ² /yr	Total O ₂ Gt/yr
Land	15*	144	21.6 (46%)*	384	57.6 (44%)
Ocean	36	72	25.9 (54%)	206	74.3 (56%)
TOTAL	51		47.5 (100%)		131.9 (100%)**

126 *Land area is contested in the present work so its productivity may be at least doubled. **It is also
127 nonsense to claim "*oceans provide every second breath of air*" because a massive atmospheric O₂ reserve
128 is 1.2 million Gt thus 131.9 Gt annual photosynthetic contribution from soil and sea combined is just
129 0.01% per year and turnover time for all O₂ in the order of 10,000 yrs – a literal 'drop in the ocean'.
130 Duursma & Boisson (1994) further state that oceans contain just 0.22% of global living biomass.

131 Oxygen, necessary for most organisms to respire, is depleted by 99.2% at the air/water boundary
132 yet it percolates throughout the soil to depth, as with rainwater, due mainly to the burrowing of
133 earthworm. The carbon productivity calculations have increasingly been revised upwards,
134 recognizing the land's larger role. Productivity values given by other authors (e.g. Whitman *et al.*

135 1998: tab. 6) are twice as high at 99 Gt total per year, whilst the satellite-derived Normalized
 136 Difference Vegetation Index (NDVI) from Field *et al.* (1998) and Stiling (1996) have 105 Gt (54% from
 137 land) and 170 Gt per year (68% from land), respectively. Most recently UNEP (2002: tab. 1.1) has
 138 Ocean vs. Land of 48.5–83 vs. 56.4–90 Pg C (totals 105–173 Gt C) (*cf.* Figure 3).



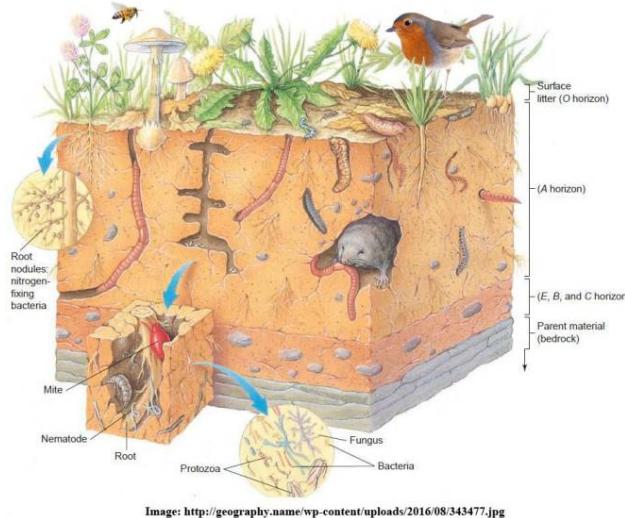
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140 **Figure 3.** Contributions of (flat) biomes to NPP (corrected in yellow); despite contrary claims,
 141 mangroves or coral reef (in red) are of minimal importance, ~2% overall. [After Campbell, N.A. &
 142 Reece, J.B. (2005:fig. 54.4a-c) from "Stiling (1996), *Ecology: Theories and Applications* (Prentice Hall)"] .

143 Primary productivity that provides for all Life on Earth operates at the biological scale of a leaf
 144 and seed or of an earthworm's burrows and castings, both around the centimetre to millimetre level.
 145 Average leaf size reportedly ranges from 0.011 to about 39.5 cm² (Falser & Westerby 2003), an
 146 earthworm's burrow is about 0.1–1.0 cm diameter (Lee 1985). However, a true range of total
 147 topographical topsoil that actually supports land plants and hosts earthworms is wanting.

148 1.3.1. Biodiversity and Biomass

149 The majority of deep carbon in soils is stored as SOM-humus composed of decaying plants and
 150 both living and dead (or dormant) animals, fungi and microbes. One cubic metre of soil may support
 151 ~200,000 arthropods, ~2,000 earthworms, countless other larger or lesser organisms plus up to 112
 152 km m⁻² of fine-roots in just the top 30 cm (Jackson *et al.* 1997). Just one gramme (about 1 cm³) of fertile
 153 topsoil may have 3 billion microbes (Bacteria, Actinomycetes, Archaea, Fungi, Protozoa, *etc.*), up to
 154 60 km of fungal hyphae, with 10,000 to 50,000 microbial species having 1,598 km of DNA some dating
 155 to the beginning of life 4 billion years ago (Fierer *et al.* 2007, Fortuna 2012, Trevors 2009, Pimental &
 156 Burgess 2013). However, all the biota totals are underestimated without terrain at scale. The figure
 157 below graphically represents this biodiversity and interdependence (Figure 4).

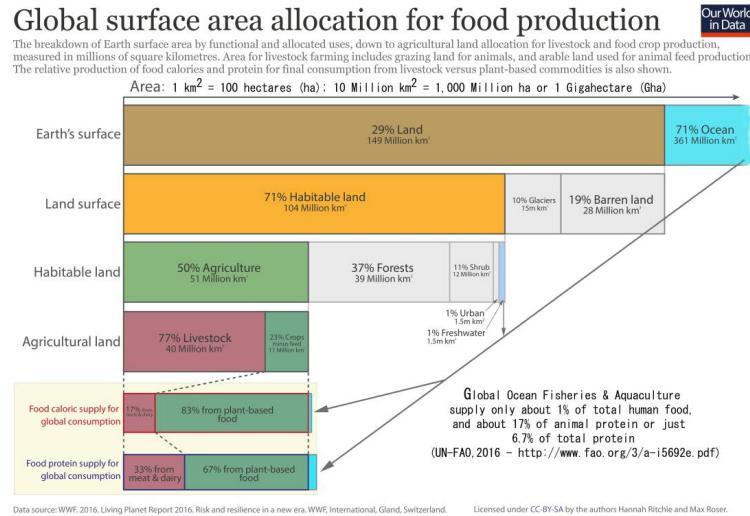


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159 **Figure 4.** Soil biodiversity, enhanced at meso and micro scales (credits in Blakemore 2018c
 160 <https://vermecology.wordpress.com>); each cm^3 of soil comprises $1,000 \times 1 \text{ mm}^3$ and so *ad infinitum*
 161 thus superficial structures of terrain and intimate or intricate details to soil depth matter greatly.

162 1.3.2. Neglected Soils and Earthworms

163 Currently, no finer resolution than kilometres, at best, seems applied to a flat global surface area
 164 of soils resulting in the following (incorrect) model (Figure 5).



165

166 **Figure 5.** Conventional land allocations (just 1% urban); while relative land proportions may not vary
 167 greatly, certainly land as a whole requires increasing for terrain. Agricultural crops also supply
 168 nutrients for aquaculture that increases yearly but is still minor (modified from Richie & Roser 2018).

169 Food comes from earthworm-rich soils that are being rapidly depleted by agrichemical farming
 170 (Blakemore 2018a). Darwin (1881: 173) estimated that earthworms annually eject in the order of 15
 171 tons per acre of surface castings on pasture/commons land ($= 33.6 \text{ t ha}^{-1} \text{yr}^{-1}$) whereas Lee (1985: tab.
 172 18) has optimal mean of $105 \text{ t ha}^{-1} \text{yr}^{-1}$ ($\times 9.5 \text{ Gha}$ of non-ice/non-desert land $= 998 \text{ Gt yr}^{-1}$ globally).
 173 Conversely, UN's FAO (2015: 103) estimates global soil formation now as just $0.15 \text{ t ha}^{-1} \text{yr}^{-1}$ while the
 174 rate under agricultural conditions ranges 0.5 to $1 \text{ t ha}^{-1} \text{yr}^{-1}$ or at most $1 \times 9.5 \text{ Gha} = 9.5 \text{ Gt yr}^{-1}$. This

175 compares to topsoil loss of 75 Gt per annum (Pimentel & Burgess 2013). Following Darwin, it is
176 generally accepted that earthworms are the major contributors to rebuilding or maintaining fertile
177 and well-drained soil (Lee 1985). However, their rate of replacement cannot keep pace under
178 relentless cultivation and poisoning due mainly to increasingly intensive chemical agriculture that
179 depletes topsoil and biodiversity. Not only populations are declining at alarming rates, several
180 earthworm species are also now extinct or likely soon to be [e.g. Blakemore 2017c, Blakemore (in
181 prep.) and the author's unpublished data].

182 **1.4. Aims of this study**

183 Despite depletion, the soil is yet key for biota, for regulation of atmospheric gases (e.g., CO₂,
184 N₂O, CH₄) – as shown in NASA's (2011) figures – it underpins primary production plus its humus is
185 the interface of adsorption/retention/rehabilitation of pollutants such as heavy metals and pesticides.
186 Due to this dependency and urgency one would think that the status of soil is well worked out as a
187 major concern. In fact, the opposite is true and more seems known about the relatively unproductive
188 and unpopulated oceans or the status of inert dirt on other planets than of the living topsoil on
189 habitable Earth. Inexplicably, the less critical spheres of air, water and space are most exquisitely
190 plotted and their research is well supported.

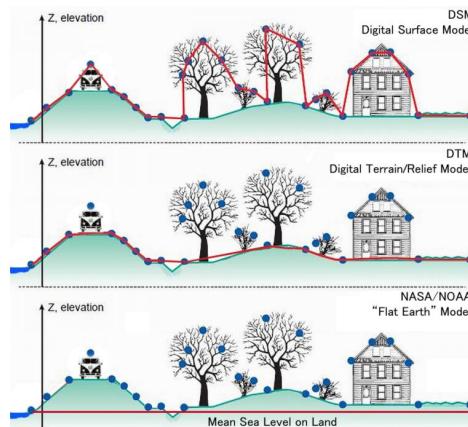
191 The present study aims to provide some initial direction to help redress this unfathomable
192 imbalance of an abysmal lack of soil ecology and lack of knowledge or information of the terrestrial
193 biome. It does not provide a definitive answer to the total surface area of land nor volume of topsoil:
194 rather, it indicates a framework for estimates and raises questions on the lack of previous
195 approximations for these basic and essential data. The soil too may require broad re-evaluation and
196 protection due to its high primary productivity, moisture relations and gaseous exchange at the
197 interface between all three elements (*viz.* soil, water and air) in its living SOM humus – the last and
198 least well-known biotic frontier (<http://science.sciencemag.org/content/304/5677>) on which our
199 knowledge needs to boldly grow. Quoting from Prof. J. Bouma (ABC 2014): "*every soil has a story to
200 tell, a fascinating story of how she was formed and how she functions in terms of potentials and limitations*".

201 **2. Materials and Methods**

202 **2.1. Theoretical Basis: Digital Elevation Models (DEMs)**

203 Aspects of terrain and scale are presented by Kamphorst *et al.* (2000). Regarding the extent of the
204 true land surface on Earth the data is currently unavailable, even standard definitions of the various
205 Digital Elevation Models (DEMs) are wanting. Despite global initiatives such as the
206 <http://globalsoilmap.net/> and a growing number of local topological projects at finer scales, a unified
207 global terrain data set remains, nonetheless, elusive due to several factors: "*largely the result of technical
208 challenges to sharing very large data sets and issues of data ownership and permissions*" (Tarolli *et al.* 2017).
209 Methodologies and technology are under development but when high resolution satellite radar data,
210 now available only to the military for resource competition, becomes more generally available then
211 accurate assessment of soil roughness over much larger surface areas will be calculable by geo-
212 morphologists and ecologists alike.

213 The theoretical basis of terrain uses models and DSM, a Digital Surface Model representing the
214 Earth's surface including all objects on it, contrasts to the 3-D Digital Terrain Model (DTM) that
215 represents bare ground surface without any objects like plants or buildings (Figure 6).



216

217 **Figure 6.** Digital Elevation Models (DEMs) include either or both DSM and DTM, as shown in this
 218 figure (modified with permission after <http://www.charim.net/datamanagement/32> : fig. 1); also
 219 shown is simplistic and unrepresentative NASA/NOAA “flat-Earth” model upon which most current
 220 global soil, biodiversity and primary productivity estimates are formulated.

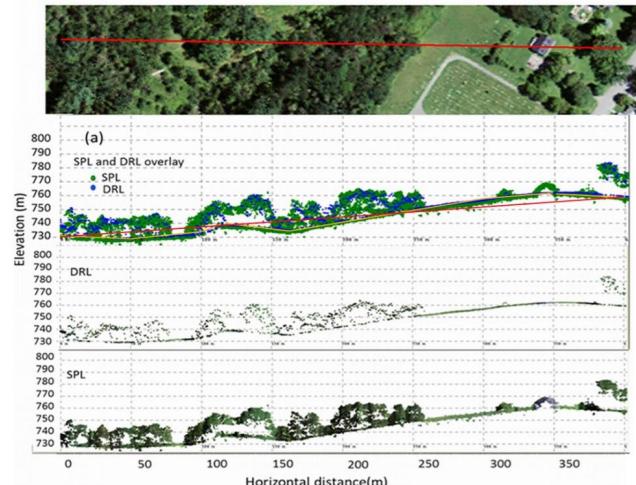
221 Essence of the present study is that compiled data for neither DTMs nor DSMs seem available.

222 **2.2. Satellites and LiDAR (laser Light Detection And Ranging)**

223 This topography deficit is surprising as the Landsat programme started in 1972 and the most
 224 recent Shuttle Radar Topography Mission (SRTM) was from 2000. Different technologies (as
 225 presented by www.charim.net/datamanagement/32) have LiDAR the most accurate, but least
 226 extensive, at scales 0.5-m or less. Nevertheless, some countries already have complete coverage from
 227 satellite data *e.g.* for Australia, China, Czech Republic, Denmark, Japan, Macedonia and USA. The
 228 UK’s Environment Agency has LiDAR DEMs for much of England most in 1–2-m resolution, some
 229 50–25-cm (<http://vterrain.org/Locations/uk/>), initially “*data for the whole country costs £56,250 plus
 230 VAT(?)*” although increasingly it is free. Unfortunately, few data are compiled into useable
 231 summaries, ideally of vegetation-free surface areas using high definition single photon LiDAR.

232 The new uncompiled data have been released with a 1 arc-second, or about 30-metres (98 feet)
 233 courtesy of NASA - www2.jpl.nasa.gov/srtm/. The Japan Aerospace Exploration Agency (JAXA)
 234 released “*ALOS World 3-D – 30m (AW3D30)*”, the global digital surface model (DSM) dataset with a
 235 horizontal resolution of ~30-m mesh (1×1 arcsecond), free of charge, in May, 2015. Another estimation
 236 of bare-earth removes vegetation from satellite data -
 237 <https://naldc.nal.usda.gov/download/38817/PDF>, but this too gives no total topography.

238 Swatantran *et al.* (2015: fig. 4) provide a methodology but give no practical example of the surface
 239 area to horizontal area. They mapped the entirety of Garrett County, Maryland, USA, covering a flat
 240 1,700 km² area but enquiries of the authors for terrain totals were to-date unanswered, while their
 241 demonstrable summary image is shown in the figure below (Figure 7).

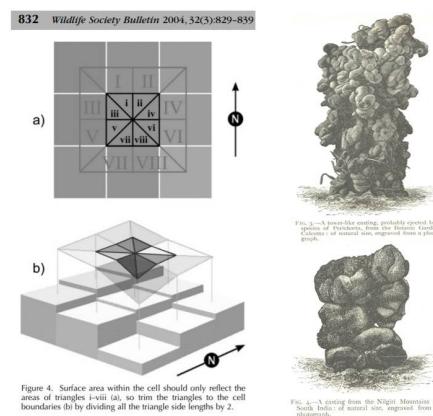


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243 **Figure 7.** Real-time photon scale LiDAR scan (modified from CC of Swatantran *et al.* 2016: fig. 4).244 **2.3. DEM Errors and Straight Line Underestimations**

245 For macro terrain a need is to find 3-D surface area to 2-D planimetric area ratio of a mapped
 246 topographic surface. Jenness (2004) says: “*There are a variety of methods in the literature for measuring*
 247 *terrain irregularity. Hobson (1972) described some early computational methods for estimating surface area*
 248 *and discussed the concept of surface area ratios. Beasom (1983) described a method for estimating land surface*
 249 *ruggedness based on the intersections of sample points and contour lines on a contour map, and Jenness (2000)*
 250 *described a similar method based on measuring the density of contour lines in an area. Mandelbrot (1983:29,*
 251 *112–115) described the concept of a “fractal dimension” in which the dimension of an irregular surface lies*
 252 *between 2 (representing a flat plain) and 3 (representing a surface that goes through every point within a*
 253 *volume). Calculating this fractal dimension can be very challenging computationally, and Polidori *et al.* (1991),*
 254 *Lam and De Cola (1993) and Lorimer *et al.* (1994) discussed a variety of methods for estimating the fractal*
 255 *dimension for a landscape. An estimate of surface area also could be derived from slope and aspect within a cell*
 256 *(Berry 2002), although Hodgson (1995) demonstrated **how most slope-aspect algorithms generate values***
 257 ***reflecting an area 1.6–2 times the size of the actual cell.** Surface area values derived with this method*
 258 *would, therefore, be unduly influenced by adjacent cells”* [my bolding].

259 Jenness (2004) mapped an area of USA of 54,850 km², but seem to not provide a 3-D area for this.
 260 Part of his method of computation is demonstrated in the figure below, in comparison to actual biotic
 261 elements such as worm casts (Figure 8).

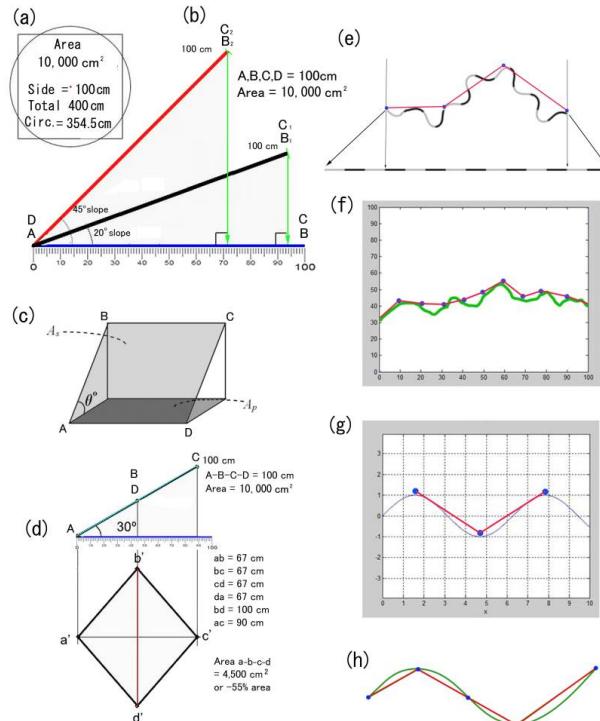


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Figure 8. Classical and, perforce, simplistic DEM from Jenness (2004: fig. 4a-b) compared to
impossible complexity of earthworm casts from Darwin (1881: figs. 3-4); straight lines are rare in
Nature and models need at least to allow for arcs, regardless if concave or convex. In reality, possibly
only laser scanning can accurately record extent and surface areas of natural events and forms. Note
too that surface casting indicate sub-surface tunneling and channeling of aerating voids.

268 A 3-D Tortuosity index is $T_i = \text{TSA}/\text{TMA}$ where TSA=Total Surface Area, TMA=Total Map Area
269 at specified scale (subscript i) but often only linear profile ratios are made of surface relief by a flat
270 Euclidean line (L_1/L_0) thus no account is taken of curved or irregular arcs. A major problem with
271 slope approximations, depending upon the algorithm used, is that ascendancies may be cancelled by
272 declines, and *vice versa*, plus the slope aspects are random and irregular with regards to any fixed
273 compass points adding yet more complexity. In other words, slope summaries are likely to be
274 considerable underestimations at the larger scale, and natural curves and convoluted distortions of
275 detail features are also unaccounted for by models. If mean model ratio value is 1.6–2.0 that means
276 increases of 60–100% are to be expected with median value 80%. Much more accurate are actual on-
277 the-ground survey data compilations. Microrelief may be further overlooked as a constant error in
278 most DEMs. Some of the concepts proposed and applied herein are illustrated below (Figure 9).



279

280 **Figure 9.** Slope or model concepts: (a) a circle and square of same area; (b) foreshortening on blue
281 base line of a sloped red or black hypotenuse (= diameter of circle or side of a square); (c) total surface
282 area (TSA) model of sloped area over actual base area; (d) projection errors for quadrat surveys unless
283 slope foreshortening is considered; (e-h) sinuous lines represent tortuous topography/relief at various
284 scales and show how straight (red) line models invariably miss curve complexity as is found in
285 Nature. Respective corrections to quadrats, the stalwarts for ecological surveys, and DEMs are
286 advocated, flagged and/or applied herein.

287 Quadrat surveys on slope may underestimate areas. Moreover, microrelief is an additional
288 consideration; for instance, earthworm burrows or castings at the cm² or less scale in a 1 m² quadrat
289 would also be considerate factor for surface relief calculations, especially since one square metre of

290 savannah or pasture may have 200–600 casts m^{-2} or even be completely composed of casts to some
291 depth, with an underlying earthworm population of up to 2,020 m^{-2} and a network of up to 888 $\text{m} \text{ m}^{-2}$
292 in length of burrow systems (= 8,880 $\text{km ha}^{-1}!$) (Kretzschmar, 1982; Lee, 1985: 90, 183, 196). Thus,
293 depending upon objectives of a study, overlooked terrain and rugosity may underestimate results
294 and even if flat spots are chosen for survey points, this ignores surrounding slope effects introducing
295 yet other errors.

296 The issue of quadrat under-sampling errors, with a worked example of terrain (of Mt Fuji) and
297 three soil area analogies (paint, kimono and the coastline paradox) are presented in Appendix A.

298 2.4. Appropriate Scales

299 Mega scale (km) is only appropriate for astronomy or hydrology. Three apparently valid finer
300 distinctions which relate to scales of observation are: land topography, soil tortuosity and soil surface
301 microrelief. Super- or sub-imposed on these is fractal porosity of topsoil humus at the micron level.
302 Macro is for 1-m calculation of terrain, biomes, and coarse properties relating to topsoils (which tend
303 to be eroded from mountains and deposited in lowland), components like carbon or earthworms and
304 primary productivity. This scale measures terrestrial life and is useful for crude Digital Surface
305 Models (DSMs). Meso (dm to cm) 1.0-0.01-m is for soil erosion, water infiltration, water storage and
306 global biomass or biodiversity assessment since terrestrial organisms mainly exist in this size range.
307 Factors interplay with those at other scales. Micro (mm) ranges 0.01–0.001-m concerns intimate soil
308 characteristics such as micro-relief, soil moisture and respiration from leaves and microbes. Sub-
309 micro is <1-mm in the μm or nm range relating to gaseous exchange, molecular reactions and the
310 microbiome. Intricacies of SOM humus are observable at this latter scale.

311 Often terms are interchangeable and standard scale measurements are ill defined. Thus uneven
312 surface areas are particularly difficult to obtain, supporting the conclusion of an International
313 Symposium that: *"On a small scale map the answer is simple, but it is not very accurate and it neglects the
314 structure of the surface completely. So then we have to decide what part of the surface roughness is to be taken
315 into account. Only those features that can be read from the map with elevation contours? Or the actual
316 roughness of the rocks and soil? Or the roughness of the sand grains and the individual pebbles? There is no
317 unambiguous answer; only an arbitrary choice is possible"* (Overbeek 1970: 3). Such considerations permit
318 an arbitrary allowance for total surface area and, in this study, observations at several scales are
319 progressively combined by adding; this is because large scale ignores microrelief and small scale
320 ignores terrain. Seemingly, this is a rather novel concept as such compiled data seems unavailable.

321 2.5. Practical and Theoretical Determination of New Land Areas

322 The first approach of this re-estimation of total land, soil and biomass figures is sought from
323 summary and extrapolation recalculations of the various published reports based upon flat-Earth
324 models; or else these values are newly determined from publically available datasets of published
325 studies (e.g. Ying *et al.*, *etc*). There are numerous studies of soil roughness or tortuosity, but actual
326 examples using true surface area examples are surprisingly rare. Online enquiries of the literature
327 and with institutions or academics over the last 8 years shows that they do not have even basic global
328 data. Personal enquiries have been made with NASA, NOAA, USGS, National Geographic, US-EPA,
329 Todai's Atmosphere & Ocean Research Institute (with over 200 staff), IGES, universities and
330 individual authors of satellite and geological surveys (Blakemore 2016c). None have been able to
331 provide even an estimate of the true undulating topography of the Earth. Apparently, Australia's

332 terrain is plotted, the first country to have this data at 1 arc-sec detail (ca. 31-m), but efforts to obtain
333 a summary from published reports or direct enquiries thus far are unanswered
334 (<https://data.gov.au/dataset/9a9284b6-eb45-4a13-97d0-91bf25f1187b>; www.ga.gov.au/metadata-gateway/metadata/record/gcat_72759).
335

336 Secondary estimates are made from theoretical DEM models, while a third approach is to reverse
337 calculate from empirical summary of total global soil carbon and soil bulk densities. Finally, a Fermi
338 estimation is made on all compiled information, as advocated by NASA (www.grc.nasa.gov/www/k-12/Numbers/Math/MathematicalThinking/fermis_piano_tuner.htm).
339

340 Throughout, SOC and SOM = Soil Organic Carbon and Soil Organic Matter that have a ratio of
341 1 : 2 (Pribyl [2010](#)). A dash is used to indicate scale of observation in land surveys, *e.g.* 1-m, 5-cm, *etc.*
342 One km² = 100 hectares (ha); 10 Million km² = 1,000 Million ha or 1 Gigahectare (Gha).
343

3. Results and Discussion

3.1. Global Terrain Recalculation

345 While raw global data is available (*e.g.* from FAO's "[Global Terrain Slope and Aspect Data](#)") this is
346 uncompiled, so an estimate of global slope is extracted from 30 arc-second resolution (*ca.* 1-km)
347 summary data provided by Nunn & Puga ([2012](#)) with mean slope for all 234 nation and dependent
348 states (excluding Antarctica) here calculated as 3.94% or nearly 4% (*ca.* 2.29°). A 4% slope is 4 cm rise
349 per metre run with the hypotenuse just 100.08 cm or an extra 0.08% length which is also an extra
350 0.08% area. Considering each country's area and slope separately about doubles this to an extra
351 0.154% land overall (as calculated in attached data file), but this is still unrealistic.
352

353 An earlier paper by Moore & Mark (1983) at 5 arc-minutes (10-km) had much lower global
354 terrestrial slope of between 0–1.5° whereas a later paper by Ying *et al.* (2014) shows such scales as
355 quite unrepresentative of the true situation. A recent 2007 calculation from USGS's [Global Slope](#)
356 [Dataset](#) of "*accurate summary statistics at 30-arc-seconds describing the underlying 3-arc-second data*" also
357 fails to yield a summary. Nevertheless, land surfaces at 1-km scales are unrepresentative so published
358 terrain data at lesser scales are presented and reviewed in the succeeding sections.
359

3.1.1. Macro: Terrain

360 Recently, Ying *et al.* ([2014](#)) claimed the first comprehensive estimate of the contributions of
361 topography to the surface-area of the whole of China using Incremental Area Coefficients (IACs) as
362 the percentage area increase of the surface area compared with the projected area. This metric is the
363 same as a tortuosity index. They highlighted scale-related factors and some potential environmental
364 revisions of natural resources and ecosystem functions when area needs are taken into account. For
365 China at 30-m resolution and a vertical error of less than 20-m they calculated a mean surface area
366 increase of 4.6% with the largest increment for a 50 km × 50 km cell being >45%. At 100-m resolution
367 the mean increase was 3.76%; at 1,000-m (1-km) it was 0.5%; while at 10,000-m it was negligible (0%).
368 Extrapolating these values linearly would give more than 4.5% increase in surface area at 1-m scale
369 (attached Excel chart). But they also clearly showed (figs. 5 & 9) that the results are exponentially
370 dependent upon scale of observation – as resolutions approach the 1-m scale the area estimates
371 increase markedly indicating threshold values for different classes of landscape below which the
372 surface-area increment caused by topographic relief cannot be ignored.
373

372 Ying *et al.* (2014) also found the mean slope of the DEM across China at the spatial resolution
 373 of 30-m was 10.92° (19.29% slope), at 100-m it was about 9° (15.84%), while at 1,000-m it was
 374 reduced to 3.53° (6.17%), and at 10,000-m it too was negligible; extrapolating this linearly would
 375 give about 12° (21% slope) at a 1-m scale for China. This compares to Nunn & Puga data that, at
 376 the horizontal scale of 30 arc-seconds (926-m), have a mean slope of China of 5.49% (3.14°) just
 377 lower than Ying *et al.*'s 1,000-m value and 3.8 times lower than the estimated 1-m value. It may
 378 thus be concluded that Nunn & Puga's values are at least 4 times underestimations of likely 1-
 379 m scale values. Nunn & Puga's overall Global average land area increase, based on slope at
 380 1,000-m resolution, was recalculated (Excel file attached) to be +0.154% of the flat area
 381 estimation, this multiplied four times to comply with an extrapolated 1-m scale from Ying *et al.*'s
 382 equivalence data, gives a value of around +0.616% overall globally. The following table
 383 summarizes these findings for Greater China (Table 3).

384 **Table 3.** Excel Recalculation for China Land Surface from Slope *vs.* Area.

Author	Scale m	Slope $^\circ$	Slope %	Total Gha	% Diff.	% means*
Ying <i>et al.</i> (projected)	1	>12	~21	0.9574	>2.23	4.52
Ying <i>et al.</i>	10	11.65	20.62	0.9562	2.10	
Ying <i>et al.</i>	30	10.92	19.29	0.9538	1.85	4.60
Ying <i>et al.</i>	100	9	15.84	0.9482	1.25	3.76
Nunn & Puga (data)	926	3.14	5.49	0.9378	0.15	-
Ying <i>et al.</i>	1,000	3.53	6.19	0.9383	0.19	0.50
Ying <i>et al.</i> (flat land)	10,000	0	0	0.9365**	0	0
% Diff. 1 <i>vs.</i> 1,000-m		>240%	~240%	2.0%	>1,074%	804%

385 *Apart from the 1-m projected value, other mean are as reported by Ying *et al.* (2014: figs. 5, 9); it is
 386 not entirely clear why their % means vary to my % Difference recalculations using their stated
 387 formula. **China's flat area from Nunn & Puga data includes Taiwan, Hong Kong and Macao, in
 388 order to agree with Ying *et al.*'s summary.

389 Milevski & Milevska (2015: tab. 1) studied real world DEMs at finer scales (5–90-m resolutions)
 390 on a patch of ground ($20 \times 20 \text{ km} = 400 \text{ km}^2$) in the Skopje area of Macedonia. They found slope
 391 accuracy increased 25 percentage points from a mean slope of 8.8° at 90-m to 11° at 5-m. This
 392 represents an increase in land area from its 400 km^2 base to 404.8 km^2 (+1.2%) and to 407.5 km^2 (+1.9%),
 393 respectively, with projection to >2% at 1-m resolution.

394 In the mountainous state of Himachal Pradesh in India, calculation by the local government
 395 (Anon. 2017: tab. 3) gave 3-D TMA of $86,384.77 \text{ km}^2$ from original 2-D MA of $55,342.79 \text{ km}^2$ or an
 396 increase of approximately 56.09%. However, resolution was at only 24-m or at 71-m scale. At finer
 397 increment – say 1-m or less – the TMA can be expected to yield a much higher figure. Tentative, true
 398 surface areas from a study using 90-m SRTM DEM for the rugged states of Jammu and Kashmir
 399 (Rashid 2010) found 3-D and 2-D areas differed by nearly 25%: “($296,513 \text{ km}^2$ *vs.* $222,236 \text{ km}^2$,
 400 respectively)”. Finer slope resolution will considerably increase the surface reality to the planimetric
 401 model, and refined rugosity more so. More real-world examples at higher scale are needed.

402 Although more accurate datasets are increasingly becoming available (e.g.
 403 www.eorc.jaxa.jp/ALOS/en/aw3d30/), it is expected that as resolution decreases from 30-m the total
 404 land may easily double at each iteration, possibly approaching 100% at 1-m scale, *i.e.*, double the land
 405 surface area to the map area. In support, a study using a $10 \times 10 \text{ km}$ plot in the Pyrenees (Nogués-
 406 Bravo & Araújo 2006: fig. 1) has actual surface area of 280 km^2 or (180% greater area with ratio of 1 :

407 2.8) at 100-m scale, more than double that of 130 km² (30%) at the 500-m scale, while at the 1-km scale
408 the surface area appears to be only about 110 km² (or just 10% larger).

409 In order to calculate the Soil Organic Carbon (SOC) in Chinese soils, Zhang *et al.* (2008) calculated
410 3-D terrain for three mountainous states. The results increased soil surface area from 2-D of 78.04
411 Mha to 3-D area value of 84.02 Mha (7.7% increase although only at coarse scale of 90-m). From this,
412 they calculated the SOC storage to 1 m depth increased from 10.9 to 11.9 Gt (+9.2%) which is of interest
413 to a later section of this report.

414 A study by Sutton & Lopez (2003) “ironed out” Colorado finding it ~12% larger (at scale of 90-m).
415

416 3.1.2. Meso: Tortuosity and Soil Roughness or Rugosity

417 The meso scale relates to an important measure of insolation defined as solar irradiance with
418 energy measured in watt-hours per square metre (Wh/m²) or in the Langley which is 1 calorie per
419 square centimetre (= 41,840 J/m²). These are both defined for horizontal area values and the latter cm²
420 scale is approximately the same size as an earthworm burrow or surface cast. This is an appropriate
421 level of observation for measuring basic ecological interactions locally and then extrapolating to a
422 global value (as is routinely done by NASA, UN, FAO, IPCC, etc.). See also
423 (www.nature.com/scitable/knowledge/library/the-soil-biota-84078125).

424 From the foregoing, it seems that tortuosity is strongly influenced by the scale factor: the more
425 intense, the higher the tortuosity index (T value). Indeed a study in Canada by Martin *et al.* (2008)
426 shows a fourfold increase in bare earth tortuosity only when resolution was reduced to less than 10-
427 cm starting from one metre scale. Martin (2008: fig. 5, tab. 1) show T_B value of 16 based upon a T_A
428 Tortuosity index of 1.2 from a TSA of 240 m² and TMA of 200 m², *i.e.*, 20% greater surface area for
429 bare soil at their 0.75-cm scale. However, it appears this study, as with several others, did not
430 adequately consider slope foreshortening which for a straight hypotenuse of about 20 m and stated
431 angle of 18 degrees gives a baseline of 19 m or 5% lesser base length. Unrealistically assuming the
432 slope is smooth and constant for its width, this then gives a simple Tortuosity Index of at least 240/190
433 = 1.26 (+26%), which is 5% above their calculation. Note that in this study [Martin 2008: fig. 5(a)], the
434 vegetated rather than bare soil hillslope had tortuosity index of about 1.5 or at least a twice as high
435 surface area as the bare earth value.

436 A study from Brazil using a 3-D laser profile scanner at intervals of 1-cm (Bramorski *et al.* 2012:
437 tab. 2) reported soil tortuosity under conventional and no-tillage with mean index (T) values of 89.62
438 and 57.4 giving an overall mean index of 73.5 or +7,250%! This tortuosity index was stated to be based
439 on that of Boiffin (1984). Communication with the author (Julieta Bramorski, email pers. comm. 11-
440 18th July, 2017) confirmed a mistake in their calculations and a new mean value of 1.33 (+33%) was
441 arrived at. Yet my re-working of the same data (kindly supplied by the primary author) gives a
442 Tortuosity index (T_i) of around 4.56 that, recalculated to allow for curved arcs rather than straight
443 hypotenuses, gave a mean T_i of 7.16 (+616%). The constant ratio between these two means is 1.57
444 (+57%) and the combined mean of these two values gives a compromise of T_i = 3.6 (or +260%). The
445 source data and Excel calculations are attached (“Julieta” section of spreadsheet data file).

446 The mean for all four independent calculations at the mm scale is +94.0%.

447 3.1.3. Micro: Biodiversity, Productivity and Respiration

448 Of two German micro scale studies, one compares different methods of measurement but
 449 provides no usable data (Thomsen *et al.* 2015: fig. A1); another (Helming *et al.* 1992: tab. 2) has mean
 450 field index value of 1.23 (*i.e.*, +23%) at 2 or 3-mm grid spacing with height accuracy better than 0.5
 451 mm. A French study at 90 x 90-mm had a mean tortuosity index around 2, *i.e.*, double relief length to
 452 same projected length or +100% (Mirazai *et al.* 2008: fig.6). Also in Europe, Kamphorst *et al.* (2000: tab.
 453 1; fig. 6) summarized the various Roughness Indices and showed tortuosity doubling or quadrupling
 454 logarithmically when scale reduces from 40-mm to 4-mm scale with mean field index around 0.35 (a
 455 slight mistake in the legend is index “ T_A ” while text has “ T_P ”) this translates as an increase of 35% or
 456 1.35 from their formulae in table 1 at this finest scale.

457 While defining Tortuosity-index as the ratio of total surface area to the map area (*i.e.*, $T_B =$
 458 TSA/MA after Helming *et al.* 1992), an Austrian report by Grims *et al.* (2014: tab. 3) at 1-mm resolution
 459 has a field value mean of $T_B = 2.63$ that implies a true surface area more than two and a half times the
 460 flat horizontal footprint (*i.e.*, +163%). [Mislabelled as “ $TB (%)$ ” in Grims *et al.* (2014: tab. 3), the primary
 461 author confirmed by email (27th July, 2017) that this is in fact the dimensionless index value not
 462 percentage]. Incidentally, this paper also measured soil organic carbon (SOC) and reported mean
 463 value of 2.0% humus (= SOM or SOC?) in the study fields.

464 An online accessible but possibly unpublished Canadian thesis has cultivated soil surface area
 465 up to almost double the flat area (1.9 m/m²) with a mean value of laser roughness at the less than 1-
 466 mm scale of 1.6 (+60%) (Koiter 2008: tabs. 2.3, 2.6, 2.7).

467 The mean value for all five mm scale results is +108.2%.

468 3.1.4. Sub-micro: SOM Surface Areas and Gaseous Exchanges

469 At the microporous scale, soil organic matter (SOM) and its colloids are reported to have
 470 adsorbic surface area for gaseous exchange of CO₂ of between 94–174 m²g⁻¹ (de Jonge 1996: tab. 2)
 471 with a mean of 130 m²g⁻¹. [This value of 130 m²g⁻¹ is used in calculations of humic SOM bulk densities
 472 below (and in an attached summary report)]. His paper quoted earlier studies showing SOM surface
 473 areas up to 800 m²g⁻¹, or six times greater, and this latter value approaches that of mineral zeolite or
 474 montmorillonite (also known as bentonite) clay. However, other studies only found 1 m²g⁻¹ (Chiou *et*
 475 *al.* 1990). The SOM data are on an “*ash free basis*”, *i.e.*, just the dry, organic content of the sample is
 476 calculated even though a non-porous, inert mineral component was present in the samples. The solid
 477 phase densities average about 1.1 gcm⁻³ (de Jonge 1996: tab. 2) and, regardless of whether from square
 478 or cylindrical measurements, the base area would be about 1 cm². The ratio of surface area (130 m²)
 479 to flat area (1 cm²) is thus approximately (10,000 x 130 =) 1.3 million times. As soil on a “flat-Earth”
 480 occupies ~12 Gha then this would theoretically have surface area also increased by 12 x (1.3 x 10⁶) =
 481 15.6 Pha. This implies that true adsorbic surface area of soil exposed to the atmosphere is almost
 482 infinitely expandable – as with the coastal paradox cited in Appendix A and as for the theoretical
 483 DTM and DSM models newly re-calculated in the section below.

484 3.1.5. Total Recalibration for New Land Surface Areas

485 Mean values from the studies reported above are summarized in this table (Table 4):-

486 **Table 4.** Chart of coarse surface topography and refined roughness (mean values of studies cited in this work).

#	Scale	Level	Area +%	Hilly	Author(s)	Applications
-	km	>1	0.0	-	NASA/NOAA	Astronomy

-	km	>1	0.0	-	Ying et al.	
1	m	1	4.5	no	Ying et al. (projected)	Terrain
2	m	1	2.0	?	Milevski & Milevska (projected)	
3	m	1	0.6	no	Nunn & Puga (recalc.)	
4	m	5	1.9	?	Milevski & Milevska	
5	m	30	4.6	no	Ying et al.	
6	m	24-71	56.1	yes	Anon.	
7	m	90	25.0	yes	Rashid	
8	m	90	12.0	yes	Sutton & Lopez	
9	m	90	7.7	yes	Zhang et al.	
10	m	90	1.2	?	Milevski & Milevska	
11	m	100	180.0	yes	Nogués-Bravo & Araújo	
12	m	100	3.8	no	Ying et al.	
13	m	500	30.0	yes	Nogués-Bravo & Araújo	
14	m	926	0.2	no	Nunn & Puga	
15	m	1,000	10.0	yes	Nogués-Bravo & Araújo	
16	m	1,000	0.5	no	Ying et al.	
0	dm	-	-	-	-	
1	cm	1	26.0	-	Martin et al. (recalc.)	Productivity, biomass
2	cm	1	33.0	-	Bramorski et al.	
3	cm	1	57.0	-	Bramorski et al. (recalc.)	
4	cm	1	260.0	-	Bramorski et al. (recalc.)	
1	mm	1	163.0	-	Grims	Soil moisture / porosity,
2	mm	1	60.0	-	Koiter	
3	mm	3	23.0	-	Helming et al.	
4	mm	4	35.0	-	Kamphorst et al.	
5	mm	90	100.0	-	Mirazai et al.	
-	µm-nm	1	Millions	-	Various	Microbiology, SOM /
			%			colloid gas exchange

487 In summary, the table above shows km scale readings are unrepresentative. The three 1-m
 488 scale projections give mean +2.38% while the mean of all 16 macro scale readings is +21.25%, this
 489 latter possibly being more applicable to more hilly terrains. For meso cm-scale the mean of all
 490 four results is +94.0%, while the five micro mm-scale results give mean of +108.2%. Thus, to a
 491 basic land flat area of 15 Gha we may apply between 2.4–21.3% increase and, to 80% of this
 492 product (equivalent to a flat 12 Gha of soil) the other two progressive increases may be overlain.
 493 Finally the approximately 20% (ca. 3 Gha) non-soil area initially subtracted, should be added to
 494 give a new total land surface, as is calculated in the options table following (Table 5).

495 **Table 5.** Summary option table of the terrain/relief results for new total land surface area.

Area increase for terrain, tortuosity and relief Gha	% diff.	x inc.
--	---------	--------

	(A) mean 1-m (n=3)	(B) mean >1-m (n=16)	(C) mean cm (n=4) %	(D) mean mm (n=5) %
(a) % increase	2.4%	21.3%	94.0%	108.2%
(b) Land 15 Gha	15.4	18.2		
(c) Soil 80% Gha	12.3	14.6		
(d) Difference	3.1	3.6		
Gha				
(e) Soil 12.3 Gha (c) x (C) then (D)			23.9	49.7
(f) Soil 14.6 Gha (c) x (C) then (D)			28.3	59.0
TOTAL (e) + Difference (d) (A)			52.8	252% \times 3.5
TOTAL (f) + Difference (d) (B)			62.6	317% \times 4.2

496 *Land total is between 52.8–62.6 Gha + 36 Gha ocean = 88.8–98.6 Gha for Earth's new total surface area.

497 As Antarctica and Greenland include sub-ice terrain then 15 Gha is a reasonable base value, the
498 tortuosity data though are for soil only which is about 80% of this outcome area (12.3–14.6 Gha).
499 Allowing for microscopic porosity, final totals may increase to much greater than 100 Gha; albeit
500 median land increase is $((3.5 + 4.2)/2) = 3.85$, or by nearly 4 times from original 15 Gha land area.

501 Combined with an immutable flat sea area of 36 Gha, this new land area of 53–63 Gha gives a
502 new world area of 89–99 Gha. This may be arbitrarily and reasonably increased with Fermi
503 calculation up to at least 100 Gha, on which a theoretically infinite SOM microporosity may be
504 superimposed, depending upon what practical calculations (e.g. biomass, NPP, gas exchange, proper
505 allocation of funds, etc.) are required and upon which set of scales is selected as most relevant for a
506 particular study or project grant application.

507 3.2. Theoretical DTM Model Calculations

508 Jenness (2008) noted slope-aspect algorithms generated indices around 1.6–2.0 (as per Hodgson
509 1995) with a median 1.8. Thus from a land surface of 15 Gha, at the metre or dm scale, this may
510 increase to 27 Gha and, as 80% supports soil, its tortuosity at the cm scale may be similarly increased
511 by 1.8 times $(27 \times 0.8 \times 1.8 =) 38.9$ Gha. It is possible to argue that the mm scale allows a further 1.8
512 times area to give a final total of $(38.9 \times 1.8 =) 69.98$ or about 70 Gha. This plus 36 Gha ocean and 5.4
513 Gha barren land $(27 \times 20\%)$ gives a theoretical new total surface area of ~111.4 Gha which is tolerably
514 close to the values (100 Gha) calculated above from on-the-ground field readings.

515 Because true surface of the land is paradoxical and depends upon arbitrary, shifting and overlaid
516 scales of observation, the most pragmatic solution is perhaps to accept a compromise Fermi value
517 pending further acuity. To transpose the scale problem it may be more practicable to arrive at a
518 reasonable working model of a global surface area (*i.e.*, the actual surface directly exposed to sunlight
519 and atmospheric gas exchange) as 100 Gha with 64 Gha attributed to land.

520 In support, a study from Germany by Hoechstetter *et al.* (2008) discusses the problem, technical
521 issues and recent developments whilst providing examples from model terrains seemingly at 1-m
522 resolution at least for test square mapped landscapes with perimeters of 400 m (but 2-D area of just
523 ca. 1,000 m² or 31.3 m side or perimeter of 126.5 m in their fig. 4?) derived from their figure 2 of square
524 patch areas (after Jenness 2004). Increases of patch areas show in their figure 4 are from 2-D of about
525 1,000 m² to 3-D of up to 10,000 m² or 20,000 m², *i.e.*, by ten or twenty-fold (or 900–1,900%). Their figure

526 4 "Average Surface Roughness" indices go from an obvious zero in 2-D up to 8 in 3-D, or by an infinite
527 amount but implied as an eightfold area increase (+700%). This gives further support for current
528 fourfold landscape increase (from 15 → ca. 60 Gha or +300%) as being entirely reasonable if not a
529 wide theoretical underestimation of total land area.

530 *3.3. DTM and DSM Recalculation*

531 Overlain upon the bare-earth terrain DTM is an increasing superficial DSM. An estimate of
532 effective DSM is possible if we apply a Leaf-Area-Index (LAI). This is a dimensionless quantity that
533 characterizes plant canopies defined as the one-sided green leaf area perpendicular to flat unit
534 ground surface area (LAI = leaf area / flat ground area, m² / m²). LAI ranges from 0 (bare ground) to
535 ~18 (dense forests) and a global average (from Asner *et al.* 2003) is 4.5. These authors state that "LAI
536 is a key variable for regional and global models of biosphere-atmosphere exchanges of energy, carbon dioxide,
537 water vapour, and other materials." It is surely just as important to have estimates of a global DTM and
538 DSM too. Prof. Greg Asner (pers. comm. email 20/7/2017) kindly clarified: "That estimate is the average
539 of studies published for different vegetated ecosystems, so it does not represent the actual global land area".
540 Thus only soil bearing terrain is considered in the following calculations.

541 As about 80% of land supports soil, on the conventional flat-Earth view and in the new view, a
542 rough estimate of prior conventional DSM is of 12 Gha × 4.5 = 54, plus 3 Gha ice-covered land = 57
543 Gha. From my new topographical calculation DSM is (64 Gha × 80% =) 51 Gha soil × 4.5 LAI = 230
544 Gha which is an important measure related to global photosynthesis potential (plus a lesser ocean
545 contribution). Since LAI is for one side of the leaf, then a total for both sides of a leaf presumably
546 gives 230 × 2 = 460 Gha DSM plus 13 Gha ice-covered land, plus 36 Gha from flat oceans = 509 Gha
547 global DSM estimate. Cities or townscapes occupy about 1–3% of flat land area with additional parks,
548 gardens, verges, *etc.* that would add but slightly to this very rough estimate of DSM. Moreover, this
549 may be an underestimation as, rather than LAI of 4.5, Whitman *et al.* (1998: 6580) assumed a leaf area
550 index more than double this at LAI = 10.

551 Microporosity will also increase the DSM since, strictly, any internal surfaces or pore spaces are
552 also part of the surface area if defined as that of solids or liquids exposed to air. Just considering plant
553 respiration, this internal areas of stomata of leaves is possibly unquantifiable. But leaves are a major
554 contributor to soil organic matter (SOM) with its micro-porous surface area for gas exchange shown
555 as between 1.5–120 Pha and an argument may be made that this is the true, 'astronomical' surface
556 area of land making the mere quadrupling of the DTM of "flat-Earth" area of just 15 Gha to 64 Gha
557 seem entirely reasonable and easily justified, as indeed is the almost 10 times increase of coarse DSM
558 from 57 Gha to 509 Gha.

559 Subterranea (*e.g.* caves, caverns or karsts) are an additional but minor 'surface' area
560 consideration, but earthworm burrows may be considerable. Burrows systems, as noted above, were
561 found to extend for up to 888 m/m² in length (= 8,880 km ha⁻¹) and their void volume varied tenfold
562 from 1.3–12.0 m²/m² ground surface in the upper 1.2 m of soil during an observation period of 1.5
563 years (Kretzschmar, 1982; Lee, 1985: 196, 208). On conventional 12 Gha flat soil this is at least 1.3 ha/ha
564 × 12 Gha = 15.6 Gha. But on rugose soil this would be about 4 times greater, *i.e.*, at least 62.4 Gha that
565 may vary up to 624 Gha or a 0.6 Tera-hectare volume of below-ground earthworm burrow voids! It
566 should be noted that the study mainly represented pasture soils in France, but the samples excluded
567 both the 0–6 cm layer of soil and also burrows <2mm in diameter (Lee, 1985: 196). Including these

568 smaller burrows and other micro pore spaces, in the topsoil especially, would presumably increase
 569 underground volumes or sub-surface spaces substantially. Nevertheless, including sub-soil voids
 570 may double the DSM to (509 + 624 =) 1,133 Gha or 1.1 Tera-hectare. The ocean surface remains at 36
 571 Gha and its bathymetry or rugosity largely an irrelevancy.

572 *3.4. Soil, C and a "Missing Sink" Soil Discrepancy*

573 Primary sources of global carbon budgets as used by IPCC (e.g. by authors such as Batjes,
 574 Haughton, Jackson & Jobbágy and Prof. Rattan Lal) invariably give a land area total of about 15 Gha
 575 on a globe of around 51 Gha. However, as this is for an idealized flat surface whereas it is self-evident
 576 that land is hilly. With topological consideration all land areas may be slightly increased at one
 577 kilometre scale (by ~1–5%) and, as already noted above, Zhang *et al.* (2008) increased soil surface area
 578 from 2-D to 3-D by 7.7% at a coarse scale of 90-m and calculated the SOC storage to 1 m depth was
 579 upped by +9.2%. As calculated above, 1-m scale projections give mean land increases of +2.38–21.25%
 580 (median about 10%), and soil carbon may certainly be increased, likely doubled or quadrupled, at
 581 finer resolutions. Factors are: soil organic carbon, roots and soil biota; justification is that these are
 582 measured at the mm to cm scale and applied at the m to km scale.

583 Lal (2008: fig. 1) cites the soil "missing sink" as 2.6 Gt/yr carbon, as discussed attached file.

584 *3.5. Total Soil Carbon (SOC + SOM) Recalculation of Global Carbon Budget*

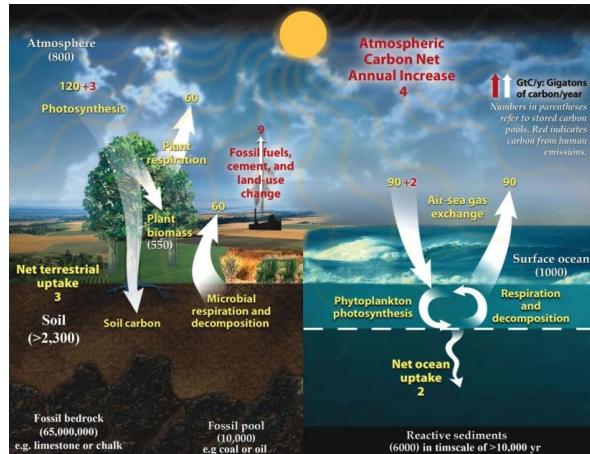
585 Relating to Greenhouse Gasses (GHGs), the table below shows carbon is the main issue
 586 (although rates were later revised by IPCC) with the problem, and the solution, to be found
 587 only in the ground (Table 6).

588 **Table 6.** Global Warming Potential (GWP) of Gasses from Duursma & Boisson (1994: tab. 3A).

Greenhouse gas GHG	Potentiality (GWP)	Emission (1990) Gt	Contribution %
CO ₂ carbon dioxide	1	26	61
CH ₄ methane	21	0.3	15
N ₂ O nitrous oxide	290	0.06	4
CFCs fluorocarbons	1,000s	0.007	9
HCFCs fluorocarbons	1,000s	0.001	0.4
Others			10.6

589

590 NASA's current convention for the carbon cycle is represented in this figure (Figure 10).



591

592 **Figure 10.** Reactive carbon cycle relating to global warming and climate change; after NASA (2011,
 593 from US DoE image as per Blakemore 2016a: fig. 4 with bedrock added); here terrestrial components
 594 are questioned as likely underestimations due to ignored surface undulation and sub-soil factors
 595 allowing productivity much higher on land than in sea. Variable gas fluxes are complex and largely
 596 irrelevant, only net soil carbon storage matters.

597 Global SOM-humus stock data are not readily available but may be calculated from global soil
 598 organic carbon (SOC) given as 1,500 Gt (by IPCC 2013, www.4p1000.org/2015,
 599 <http://www.fao.org/3/a-i6937e.pdf> 2017, Lal 2008), 2,300 (by NASA 2011), 2,397 (by Carvalis *et al.*
 600 2014) or as 2,956.5 that is quoted as ~3,000 Gt (Köchy *et al.* 2015). Value differences are largely due to
 601 depth of topsoil sampling (Blakemore 2016 a, 2017), the first is 0–1 m, the second is 0–3 m, and the
 602 third and fourth most recent values include soil greater than 1 m (Köchy *et al.*, 2015 who possibly
 603 have mean 4.0 m for peats or to depth of soil for other types?). Then, taking the higher value of 3,000
 604 Gt and applying the revised van Bemmelen factor of SOM = 2 x SOC (Pribyl 2010), the total SOM is
 605 6,000 Gt on a dry-weight or an “ash free basis”. However, all values are for ‘flat-Earth’ calculations
 606 of just ~12 Gha soil area having a SOM bulk density (BD) of 6,000/120,000 = 0.05 tm^{-3} , and if this is
 607 doubled for terrain and coarse relief then the total topsoil mass is presumably increased too, that is,
 608 for SOC from 3,000 → 6,000 Gt and for SOM humus 6,000 → 12,000 Gt with a new SOM bulk density,
 609 keeping same area due to fixed core sample volumes, as 12,000/120,000 = 0.1 tm^{-3} the significance of
 610 which is noted in BD section below.

611 In addition to terrain considerations, Blakemore (2016a: 11) noted that: “Soil carbon values require
 612 allowance for intractable glomalin adding a further 5–27% to almost all SOC tallies (Comis, 2002). Plus data
 613 from deep soils may increase budgets: e.g., Harper & Tibbett (2013) found C up to five times greater in
 614 Australian soils at depth >1 m and down to 35 m in some cases. The Walkley-Black method itself
 615 underestimates total C by about 20% with a correction factor of ca. 1.3 often required [this W-B correction is
 616 from Pribyl, 2010], whereas latest techniques using mid-infrared (MIR) spectroscopy give more accurate
 617 readings. These three factors combined would surely increase soil SOC totals.”

618 Thus, assuming soil depth factors are already included with terrain area, 6,000 Gt SOC x 1.3 W-
 619 B correction = 7,800 Gt plus, say, median value 10% for glomalin = 8,580 Gt total soil carbon.
 620 Worldwide, the reactive organic carbon stored in soils (herein from 3,000 → 8,580 Gt) thus greatly
 621 exceeds the most generous amounts attributed in above-ground phytomass (700 Gt), plus atmosphere
 622 (800 Gt) and surface oceans (1,000 Gt) which combined equal just 2,500 Gt.

623 Global topsoil SOM-humus is then also raised from 8,580 SOC x 2 to approximately 17,160 Gt
624 (but as calculated below, to greater than 1 m depth this may be doubled again to ~34,320 Gt).

625 Turnover time for fast pool carbon is estimated as 23 years (Carvalis et al. 2014) cf. 10–15 yrs
626 according to IPCC (2007). These then would also be duration for processing of humic SOM by
627 saprotrophic/detritivore earthworms, as indeed Darwin (1881) extrapolated from his minute
628 observations: “*All the fertile areas of this planet have at least once passed through the bodies of earthworms.*”
629 From this Blakemore (2016a) reasoned that all atmospheric carbon is theoretically processed through
630 the intestines of earthworms in ~12-year cycles. That is, unless populations are depleted (Blakemore
631 2018).

632 *3.6. Bulk Density (BD) Backcheck*

633 Support for the terrain argument is from bulk density (BD) that compels revision. Tangible sub-
634 samples are taken on the ground at fixed core sample volume with a constant planimetric area (cm^{-2}
635 or m^{-2}) and multiplied by a biome’s area, thus mass may be adjusted to comply only by adding biome
636 area by adding biome terrain/relief.

637 For habitable biomes supposedly totaling 12.3 (flat) Gha, Whitman et al. (1998: tab. 2; [Ref](#)) gave
638 mean soil bulk density as 1.3 gcm^{-3} ($= \text{tm}^{-3}$) and Lee (1985: 195) assumed a bulk density of 1.4 gcm^{-3}
639 so a reasonable mean may be 1.35 gcm^{-3} . Total SOC to one metre recalculated (from HWSD as in
640 attached data file) gives median values for SOC of around 1.3% and their mean soil BD is $\sim 1.4 \text{ gcm}^{-3}$
641 (close to 1.35 gcm^{-3}). Total conventional “flat-Earth” topsoil mass to 1 m depth would then be $[(123 \times$
642 $10^{12} \text{ m}^3) \times 1.35 \text{ tm}^{-3} = (166 \times 10^{12} \text{ t})] = 166,000 \text{ Gt}$ topsoil and 1.3% SOC = 2,158 Gt globally, allowing
643 that organic soils have lower BD than mineral soils.

644 Highly organic, peaty Histosol SOM BD is 0.1 gcm^{-3} (Köchy et al. 2015: 354) and prior best
645 estimate of total SOC to 1 m depth by IPCC, 4p1000.org, etc. was 1,500 Gt giving total $\times 2$ SOM of
646 3,000 Gt on planimetric 12 Gha land or $120,000 \text{ m}^3$ to 1 m depth, thus a BD of $(3,000/120,000 \text{ Gt/Gm}^3$
647 $=) 0.025 \text{ gcm}^{-3}$. This is below the required SOM BD of 0.1 gcm^{-3} and thus needs $\times 4$ mass. The only
648 plausible way to increase mass is by increasing real biome area to allow for terrain. When the soil
649 surface is doubled for terrain and again for micro-relief then mass of soil increases. Since BD
650 measurements typically use a core cylinder of fixed volume thus the actual undulating surface area
651 is immaterial. For demonstrative purposes of real BD, if we assume quadruple SOM $3,000 \rightarrow 12,000$
652 Gt, whilst maintaining 12 Gha planimetric area (or its volumetric equivalent to 1 m depth), bulk
653 density is 0.1 tm^{-3} matching the required mean of 0.1 tm^{-3} (Q.E.D.).

654 Is it reasonable to increase land values fourfold? Given a BD mean of 1.35 gcm^{-3} (or tm^{-3}) and
655 allowing for a fourfold increase in soil occupied land area (i.e., 12 Gha $\times 4 = 48$ Gha), then total soil
656 mass to 1 m would be $(480,000 \text{ Gm}^3 \times 1.35 \text{ t}) = 648,000 \text{ Gt}$ globally. If SOC is 1.3% then total SOC to 1
657 m is 8,424 Gt that tolerably agrees with the 8,580 Gt value calculated above.

658 Similarly, a planimetric soil area of 12 Gha to 3 m depth ($= 360,000 \text{ Gm}^3$) requires a new SOM of
659 36,000 Gt to give the required 0.1 gcm^{-3} . If 3 m SOC doubled from 8,580 $\rightarrow 17,160 \times 2 = 34,320 \text{ Gt}$ SOM
660 giving BD of $(34,320/360,000 =) 0.095$ or tolerably 0.1 gcm^{-3} (Q.E.D.). However, both bulk density and
661 SOC % means are certain to be less reliable at depths greater than 1 m.

662 Another calculation, possibly artifactual, is with prior SOC > 1 m depth (Köchy et al. 2015) of
663 3,000 Gt $\times 2$ for 6,000 Gt SOM on planimetric 12 Gha if to a sample depth of 3 m = $360,000 \text{ Gm}^3$ giving
664 real SOM bulk density of just 0.016 tm^{-3} or out by a factor of six for average BD of peaty SOM of

665 around 0.1 tm^{-3} . This discrepancy may be resolved with reference to terrain/relief by about x 6 from
 666 flat 12 Gha to approximately 72 Gha that, plus 3 Gha deserts and 36 ocean, gives total surface area of
 667 111 Gha. Seeming slightly excessive this may be ultimately reasonable and is, coincidentally, exactly
 668 the same value of 111.4 Gha arrived at earlier with the theoretical DSM model.

669 The standard BD reference is planimetric 12 Gha to the centre of the Earth and overlaying
 670 this is is terrain and soil relief, *etc.* Using multiplication factors, the following table summarizes
 671 possible area scenarios for SOC at soil depths (assuming mean BD 1.35 gm^{-3} and SOC of 1.3%)
 672 (Table 7).

673 **Table 7.** Summary of the possible terrain areas from mean bulk density (BD) with SOC mass (Gt).

BD tm^{-3}	Area Gm^2	Factor	Soil Gt	Depth m	SOC @ 1.3%	Cf. 1,500 Gt
1.35	120,000	x 1	162,000	1	2,106	x 1.4
1.35	240,000	x 2	324,000	1	4,212	x 2.8
1.35	480,000	x 4	648,000	1	8,424	x 5.6
1.35	720,000	x 2	972,000	3	12,636	(x 4.2 cf. 3,000)
1.35	720,000	x 4	1,944,000	3	25,272	(x 8.4 cf. 3,000)

674

675 This table shows IPCC's current conventional 1 m SOC estimates (of *ca.* 1,500 Gt) are thus out by
 676 factors between 1.4–5.6 times. Terrain x factors are for coarse landforms, and also for superficial cm^2
 677 + mm^2 relief details that, at both scales, are mainly composed of SOM-humus/earthworm casts.

678 For reference (from Wikipedia), amorphous carbon densities are 1.8–2.1 gcm^{-3} differing from dry
 679 soil bulk density that varies in its minerals, biotic as well as its air space voids (porosity).

680 Although revealing conventional underestimations of SOC/SOM, these variable results from BD
 681 calculations probably relate to difficulties in obtaining global BD means and their complexity with
 682 soil depth. Perhaps the upper 1 metre results are most reliable. Full calculations and justification for
 683 bulk density are provided in an attached file.

684 *3.7. Root Stocks, Vesicular-Arbuscular Mycorrhiza (VAM) Hyphae, Litter and Earthworms*

685 Relating to above-ground vegetation are the often ignored underground root-area-indices
 686 (RAIs) with fine roots a prominent sink for carbon, often much greater than that of vegetation above
 687 ground: Jackson *et al.* (1997) estimated average fine root biomass between 0.3–1.5 kg m^{-2} and total root
 688 biomass of 292 Gt containing 146 Gt carbon (from Jackson *et al.* 1997: tabs. 2–3 data) and representing
 689 33% of total annual net primary productivity. However, this was updated by Mokany *et al.* (2005: 95)
 690 to 241 Gt C for roots. It was also shown that perhaps 50% of below-ground allocation is released as
 691 extra-root carbon exudates (Bolinder *et al.* 1997). Moreover, UNEP (2002: 10) estimate that probably
 692 over 80% of plant production enters the soil system either through plant roots or as leaf litter-fall.
 693 Extending many metres below ground and interlinked with kilometers of symbiotic VAM fungal
 694 hyphae, roots are routinely excluded from soil samples by manual removal and sieving. Additionally,
 695 Robinson (2004) estimates at least 15 Gt C for soil mycorrhizal hyphae. Some vegetation surveys, but
 696 certainly not all, make allowance for below ground biota and for living or dormant biomass and dead
 697 necromass.

698 Generally excluded from calculations of SOC (and SOM) mass calculations, leaf-litter – an
 699 important part of the soil profile transitioning to humus – contributes considerably to the global
 700 carbon budget with a “*pedologic pool*” of 40–80 Gt with median 60 Gt (Batjes 1996; Lal 2008: fig. 1).

701 Thus additional soil carbon strictly includes larger root mass (241 Gt), leaf-litter (60 Gt), plus
 702 VAM (15 Gt) and earthworms (4 Gt from Blakemore 2017) to total 320 Gt that may all be reasonably
 703 doubled to allow for terrain to (320 x 2 =) 640 Gt carbon. This, may then be added to the SOC-based
 704 17,160 Gt SOM to >1 m soil depth to give new total SOM of about 17,800 Gt (as in Abstract).

705 *3.8. Biotic Carbon: Living, Dormant or Dead (Including Fossils and Geology)*

706 Regarding biotic carbon (most of which is included in SOC data), a much-cited study (Whitman
 707 *et al.* 1998: tab. 5) of prokaryotes [*viz.* Monera (simple bacteria) and Archaea] estimated their total
 708 cellular carbon biomass as up to 450 Pg (= 450 Gt) that they claimed equaled the carbon storage in
 709 land plants. Their allocation of prokaryotic mass was approximately 50 : 50 ocean to land (actually
 710 48–241 Gt carbon in soil versus 305.2 in sea). But their table 2 of land estimates, although to 8 m depth,
 711 is for flat-earth biome areas (they say totals 12.3 Gha excluding ice) multiplied by numbers of microbe
 712 cells sampled from each biome; whereas for ocean in their table 1 it is unit volume of sea (cells/ml)
 713 thus immutable. It is likely that terrain/relief will similarly at least double the land count and thus
 714 the total biomass by at least one third. Taking their upper 241 Gt value x 2 for terrain and x 2 for relief
 715 = 964 Gt in soil, plus 305.2 in sea = 1,269.2 Gt total biotic carbon. However, a recent ocean re-
 716 assessment (Kallmeyer *et al.* 2012) reduced microbial biomass on the seafloor due to paucity in actual
 717 deep ocean cores from their original 303 billion tonnes of C to just 4.1 billion tonnes representing just
 718 0.6% of Earth’s total living biomass and reducing the total global biotic carbon to about 970 Gt with
 719 most (*i.e.*, 966 Gt) in soil. Thus land’s allocation is yet again greatly enhanced disproportionately to
 720 that of the ocean.

721 The UNEP (2002: tab. 2.1) “*World Atlas of Biodiversity*” despite claiming global coverage is mainly
 722 concerned with marine/ocean/water and barely mentioned soils, nevertheless, had total carbon content
 723 of Earth as ~100,000,000 Gt C, allocated as in the following, modified and corrected, tables (Tables 8-9).
 724

725 **Table 8.** Revised reactive-recyclable and non-reactive (stored) carbon after UNEP (2002: tab. 2.1).

Global carbon	Stored C Gt	Reactive (biotic and inorganic) C Gt
Sedimentary rock organic C	16,000,000	
Sedimentary rock carbonate	65,000,000	
Dissolved inorganic C in deep sea	40,000	
Organic carbon in deep sea	1,350	
Reactive inorganic C in surface sea		*1,000
Organic carbon in soil (0-1 m)		**8,600
Atmospheric CO ₂ – C		800
Biomass in + on land (plants + micro)		***2,000
Biomass in sea		***15
TOTAL	81,041,350	12,415

726 Notes: *Sundquist & Visser (2003: fig. 1) show only surface sea carbon is reactive in yearly to decade
 727 intervals, whereas most ocean carbon is un-reactive to the atmosphere for centuries, millennia or up to
 728 geological timescales. **The soil carbon estimates, originally at 1,500 Gt, are upped to 8,580 Gt to allow
 729 for microbes + terrain; values at >1 m depth may double this. ***Originally 560 Gt, the present land total

730 accounts for roots and sub-soil biota both doubled for terrain; sea biomass of "5-10" Gt is updated with
 731 values as noted in tables of the following section.

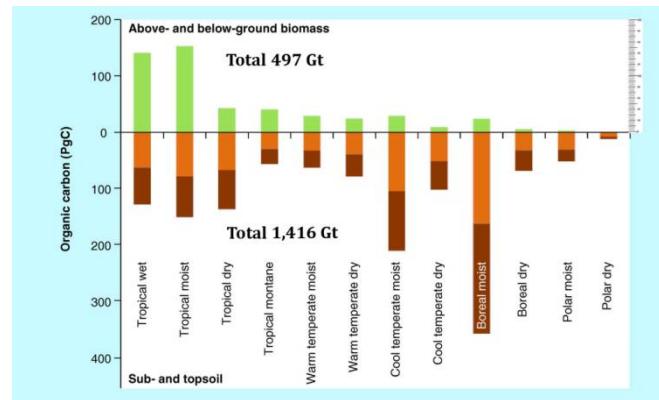
732 **Table 9.** Above tabulated data combined with that from Duursma & Boisson (1994: tab. 2) for total amounts of
 733 primary elements of total carbon and gaseous oxygen (with relative % proportions).

Medium	Carbon C Gt (%)	Oxygen O ₂ Gt (%)
Air	6.4×10^2 (0.00%)	1.2×10^5 (99.2%)
Land (mainly in rocks)	8.1×10^7 (99.96%)	NA*
Sea	3.5×10^4 (0.04%)	9.8×10^3 (0.8%)
TOTAL	8.1×10^7 (100%)	1.21×10^5 (100%*)

734 *Oxygen in rocks is substantial but unknown; on average about 25% topsoil volume is aerated,
 735 lessening to the depth of working of earthworms (~15 m); but life occurs on land up to 19 km deep
 736 (e.g. www.astrobio.net/extreme-life/life-might-thrive-dozen-miles-beneathearths-surface/).

737 3.9. Above and Below-Ground Biodiversity and Biomass Carbon Rechecked (plus Ocean C)

738 It is remarkable that almost always overlooked or undervalued in biodiversity assessments are
 739 the communities and networks of below-ground soil biota that represent both the Earth's highest
 740 diversity and its greatest biomass (even without consideration of terrain effects) (Figures 11-12).
 741



742

743 **Figure 11.** After Scharlemann *et al.* 2014: tab. 1, fig. 3 - (CC - www.tandfonline.com/terms-and-conditions) of terrestrial organic carbon in twelve IPCC-defined climatic regions in above-
 744 (phytomass) and below-ground (soil carbon to 1 m depth). Both these totals increase substantially
 745 when terrain and relief are taken into consideration as already shown herein. Flammable above-
 746 ground trees or grasses are not major C stores as is often claimed.
 747

Taxon		Mass Gt C = 10 ¹⁵ g C	Abundance
Plants	Trees	450	10 ¹³
Bacteria	Terrestrial deep subsurface	60	10 ³⁰
	Marine deep subsurface	7	10 ²⁹
	Soil	7	10 ²⁹
	Marine	1.3	10 ²⁹
	Total	70	10 ³⁰
Fungi		12	10 ²⁷
Archaea	Terrestrial deep subsurface	4	10 ²⁹
	Marine deep subsurface	3	10 ²⁹
	Soil	0.5	10 ²⁸
	Marine	0.3	10 ²⁸
	Total	7	10 ²⁹
Protists		4	10 ²⁷
Animals	Chordates	Fish	0.7 (0.5)
		Livestock	0.1
		Humans	0.06
		Wild mammals	0.007
		Wild birds	0.002
	Arthropods	Terrestrial	0.2
		Marine	1
		Annelids	0.2 (0.82)
	Molluscs		0.2
		Cnidarians	0.1
		Nematodes	0.02
	Total		2 (2.42)
Viruses		0.2	10 ³¹

748

749 **Figure 12.** Latest global biomass estimate (Bar-On *et al.* 2018) modified in red (as acknowledged by
 750 author Dr Ron Milo pers. emails 16th July, 2018), that totaled ~545.2 Gt C with 97.2% terrestrial vs. 2.8%
 751 oceanic; compare to data by Duursma & Boission (1994) with about 99.78% land vs. 0.22% sea for
 752 Earth's total living organisms. In contrast, Dr Sylvia Earle (2009
 753 <https://oceantoday.noaa.gov/sylviaeаре/>) claims ocean as "home for about 97% of life in the world, maybe
 754 in the universe." The present study quadruples their land biomass total to above 2,000 Gt C.

755 Most calculations of terrestrial fauna and flora (plants, microbes and animals) based upon flat-
 756 Earth biomes or habitats require revision and likely doubling or quadrupling and this affects relative
 757 ocean proportions. Although the total animal biomass appears to be insignificant in comparison to
 758 land plants (UNEP 2002: 11) just considering megadrile earthworms, recent calculations (Blakemore
 759 2017) of 1.3 quadrillion worms with fresh weight biomass 4–8 Gt, may be doubled for terrain relief to
 760 2.6 quadrillion and a staggering 8–16 Gt (with carbon content up to 4 Gt). If correct, earthworms
 761 would be truly significant (as Darwin, 1881 surmised) even though they are apparently in decline
 762 (Blakemore 2018). Comparing this to a recent best estimate of global fish "wet weight" of just 1–2 Gt
 763 (Wilson *et al.* 2009) (carbon at most 0.5 Gt) that casts glib comments about worms being good fishing
 764 bait in a whole new light.

765 Terrain increase has most significance to smaller, superficial microbes and Arthropoda (mainly
 766 insects) but has less relevance for colonial soil societies such as ants or termites with concentrated
 767 and localized nests or mounds rather than individuals being widely and deeply dispersed as indeed
 768 are earthworms.

769 Life on Earth may be similarly elevated as summarized in carbon calculations above. However,
 770 (as noted), an ignored sub-surface biomass (the rhizosphere of VAM fungi and roots) substantially
 771 increase the land proportion (Mokany *et al.* 2005, Jackson *et al.* 1997).

772 For roots Mokany *et al.* (2005: 95) said: "Our results yield an estimated global root stock of 241 Pg C,
 773 a similar value to that proposed by Robinson (2004), but about 50% higher than the 160 Pg C estimated by
 774 Saugier *et al.* (2001). This dramatic increase in estimated global root carbon stock corresponds to a 12% increase
 775 in estimated total carbon stock of the worlds vegetation (from 652 to 733 Pg)". Searching their sources, the

776 value 652 Pg is likely above-ground vegetation from Saugier *et al.* (2001) of 492 Pg, plus Robinson's
 777 ([2004](#)) estimate of 160 Pg root ($492 + 160 = 652$). And 733 is seemingly from the same above-ground
 778 value plus their own estimate of 241 Pg root carbon ($492 + 241 = 733$ Pg = Gt).

779 Thus a total of above- and below-ground land vegetation are reasonably accepted as 733 Gt C
 780 which, along with bacteria from Whitman *et al.* ([1998](#): tab. 5) and as re-assessed by Kallmeyer *et al.* ([2012](#))
 781 of 241 Gt *vs.* 6.3 Gt in soil *vs.* sea, respectively, gives biomass carbon on land of ($733 + 241 =$) 974 Gt.
 782 Robinson ([2004](#)) estimates at least 15 Gt C for soil mycorrhizal fungal hyphae that may be partly
 783 excluded by sieved samples ($974 + 15 = 989$), plus 4 Gt earthworms and 7 Gt for other organisms (from
 784 Bar-On *et al.* 2018) = 1,000 Gt total. This terrestrial carbon may yet be doubled for terrain (and possibly
 785 doubled again for soil relief, especially for microbes) to give between 2,000–4,000 Gt land C plus an
 786 ocean contribution of just 14.8 to total at least 2,014.8 Gt living biotic carbon (Table 10).
 787

788 **Table 10.** Revised global biotic carbon on and in the soils on land and in the sea.

Biota	Soils Gt C	Sea Gt C
Plants above ground	492	
Roots	241	
Bacteria	241	6.3
VAM hyphae	15	
Earthworms	4	
Fish*		0.5
Other organisms**	7.0	8.0
TOTAL (%)	1,000 (98.6%)	14.8 (1.4%)
TOTAL x 2 for terrain (%)	2,000 (99.3%)	14.8 (0.7%)

789 *Global fish stocks confidently calculated as 0.89–2.05 Gt wet weight ([Wilson 2009](#)) of which just 0.15
 790 Gt (~10%) total annual combined fish catch and aquaculture
 791 (https://en.wikipedia.org/wiki/World_fisheries_production) still the highest on record to date; fish
 792 carbon is 0.5 Gt C. **Other organisms from Bar-On *et al.* (2018). Thus over 2,000 Gt of living biomass is
 793 terrestrial while just 15 Gt is in the sea; or >99% is on or in soil and just <0.7% in sea.

794 As carbon is universally about 50% dry weight, a new value is ($2,000 \times 2$) = 4,000 Gt dry mass on
 795 land plus (14.8×2) = 29.6 Gt in sea. Since water content is taken as 50% [\sim 30% in wood ([www.wood-
 796 database.com/wood-articles/wood-and-moisture/](#)) and 40–70% in bacteria (Ross & Billing [1957](#),
 797 Kirschner [2018](#)) with median value ~50%] then this value is doubled again to ~8,000 Gt wet weight
 798 on land plus ~60 Gt in sea to give new total for Earth's living, respiring, fresh mass of ~8,060 Gt, or
 799 roughly ~8 Tera-tonnes (Tt) of biomass.

800 These data compare to Smil ([2011](#)) of total dry biomass of Life on Earth he estimated as just 1,600
 801 Gt (here more than doubled to at least 2,000 Gt, maybe 4,000 Gt). As a cross-check, the total carbon of
 802 the biosphere is estimated at between 1 to 4 Trillion tons ([AGCI 2018](#)), with my current estimate of
 803 around 2,000 Gt C (2 Tt) about mid-range but closer to the best case scenario.

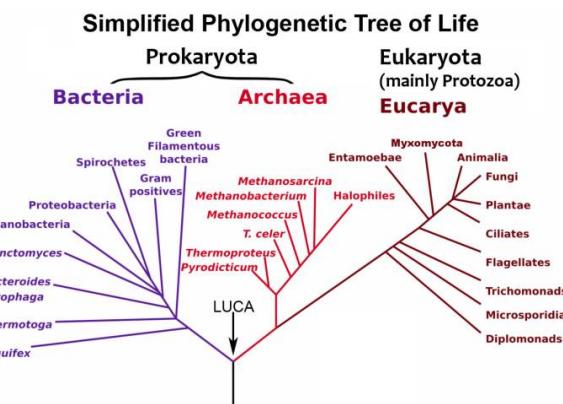
804 Total terrestrial carbon is thus estimated as at least 2,000 Gt in land organisms most intermixing
 805 with the 8,580 Gt in SOC in SOM or humus as active carbon stored and recycled on land, compared
 806 to just 900–1,000 Gt reactive carbon in the oceans ([NASA 2011](#), Lal 2008: fig. 1). Observable today, as
 807 in the geological past, is how biologically active compost (part of humus) rapidly recycles organic
 808 remains, hence one reason why topsoil leaves few soft tissue fossils compared to water submersion,

809 anaerobic inundation, or mud that all stifle decomposition and give rise to fossils and bio-
810 sedimentary rocks.

811 *3.10. Biodiversity of Species*

812 Concomitant with the increasing detail of terrain is a realization that the biological scale of life
813 on earth is also increasingly refined to reduce the major living components from the scale of giant
814 trees and massive mammals, to that of invertebrates, and finally to the microbial components that,
815 on most recent revisions, have the largest biomass, biodiversity and contributions to biotic energy
816 cycles. As Ying *et al.* (2014) succinctly state: *"The increase in [land] surface area with spatial resolution
817 should mean more living space and a more diversified environment for smaller sized organisms, which comprise
818 the majority of species (and thus contribute more to biodiversity). This trend also leads to underestimation of
819 the role of environmental processes occurring at finer scale."*

820 While the present recalibration makes only a moderate difference to habitable land at the metre
821 scale – that is, for large animals like humans and their livestock or for large plants – it makes a greater
822 change to habitat space for organisms in the realms of the cm scale (for example fungi, larger insects
823 and earthworms) and a massive difference for the majority of animals and plant life that are measured
824 in mm or less down to the micrometre (μm) microbe scale. Especially the hordes of autotrophic,
825 heterotrophic, symbiotic and parasitic microbes, including fungi, that already dominate the Earth
826 and exist mainly in the living soil (Figure 13).



827

828 **Figure 13.** A phylogenetic tree of living things, based on RNA data and proposed by Carl Woese,
829 showing the separation of Bacteria, Archaea, and Eukaryota (source:
830 https://en.wikipedia.org/wiki/File:Phylogenetic_tree.svg based on Woese *et al.* 1990).

831 Below are conventional global biodiversity and biomass calculations (Figures 14–15).

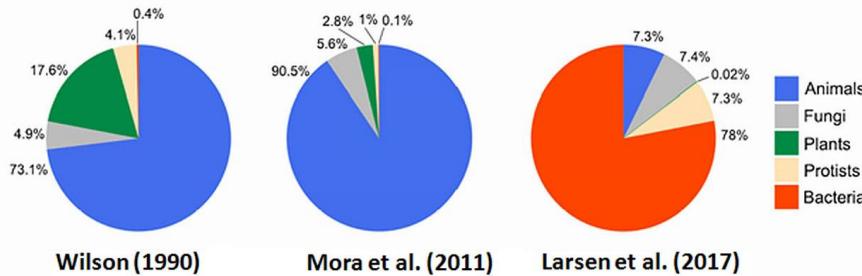
Species	Earth			Ocean		
	Catalogued	Predicted	±SE	Catalogued	Predicted	±SE
Eukaryotes						
Animalia	953,434	7,770,000	958,000	171,082	2,150,000	145,000
Chromista	13,033	27,500	30,500	4,859	7,400	9,640
Fungi	43,271	611,000	297,000	1,097	5,320	11,100
Plantae	215,644	298,000	8,200	8,600	16,600	9,130
Protozoa	8,118	36,400	6,690	8,118	36,400	6,690
<i>Total</i>	1,233,500	8,740,000	1,300,000	193,756	2,210,000	182,000
Prokaryotes						
Archaea	502	455	160	1	1	0
Bacteria	10,358	9,680	3,470	652	1,320	436
<i>Total</i>	10,860	10,100	3,630	653	1,320	436
Grand Total	1,244,360	8,750,000	1,300,000	194,409	2,210,000	182,000

Predictions for prokaryotes represent a lower bound because they do not consider undescribed higher taxa. For protozoa, the ocean database was substantially more complete than the database for the entire Earth so we only used the former to estimate the total number of species in this taxon. All predictions were rounded to three significant digits.

doi:10.1371/journal.pbio.1001127.t002

832

833 **Figure 14.** Table of biodiversity from Mora *et al.* 2011 (ex Wikipedia from
834 https://en.wikipedia.org/wiki/File:Mora_2011_Predicted_and_Unpredicted_species.png); this shows
835 that land has much higher biodiversity than oceans: 1.2 v 0.19 million taxa despite the oceans being
836 better surveyed and catalogued than soils following CoML 2010 (<http://coml.org>) .



837

Wilson (1990) Mora et al. (2011) Larsen et al. (2017)

838

839 **Figure 15.** Progressive estimates of the proportions of biota showing our fundamental lack of
840 knowledge of Life on Earth, especially of the bacteria and fungi that are dominant in many soils
(modified from Larsen *et al.* 2017) .

841

842 While about 2 million species have been formally described, (Larsen *et al.* 2017) global
843 biodiversity recently revised to consider the unique symbionts and parasites of animals produced a
844 new “pie of life” of up to two billion species *in toto* (see figure), a thousand times increase. Some other
845 estimates using scaling laws to predict species go as high as a trillion taxa when all virus and microbes
846 are tallied (Locey & Lennon 2016). All these estimates too are based upon the “flat-Earth” model and
847 thus require up-scaling for terrain, relief, *etc.*

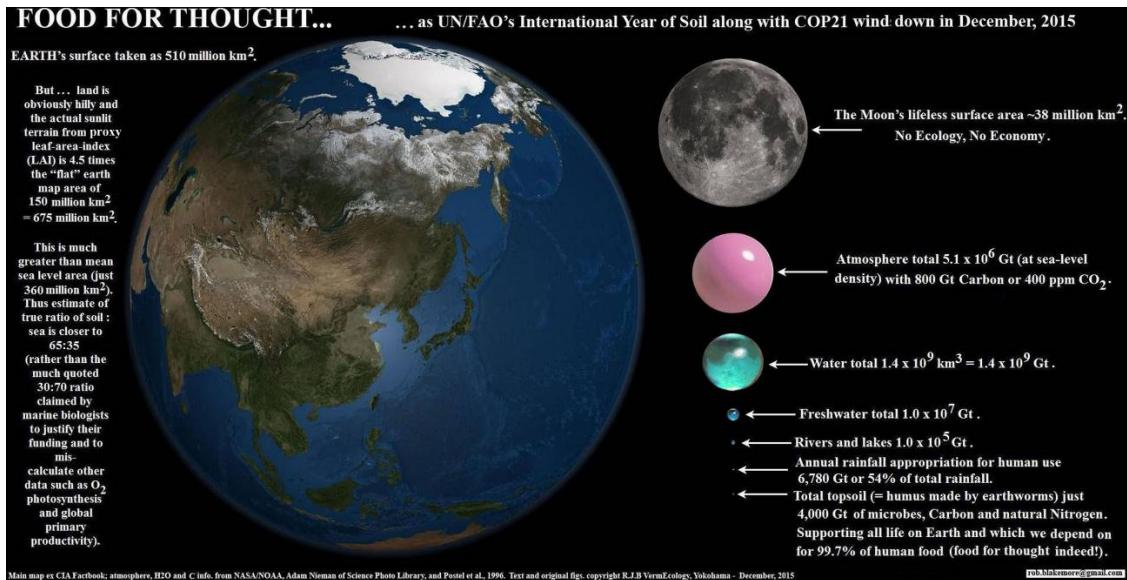
848

3.11. Topsoil Resource

849

850 Returning to the initial questions about the Earth’s organic topsoil. It is vitally important is to
851 determine and to conserve this vital resource or, as Darwin (1881: 39) has it in his swansong book on
852 Earthworms: “*The vegetable mould [= topsoil humus] which covers, as with a mantle, the surface of the*
853 *land...*” Soils occupy 81% of land that is not (yet) extreme desert, rock, sand, ice, or waterlogged (19%)
(Jackson *et al.* 1997: tab. 2) and its frailty is as visualized in the following figure (Figure 16).

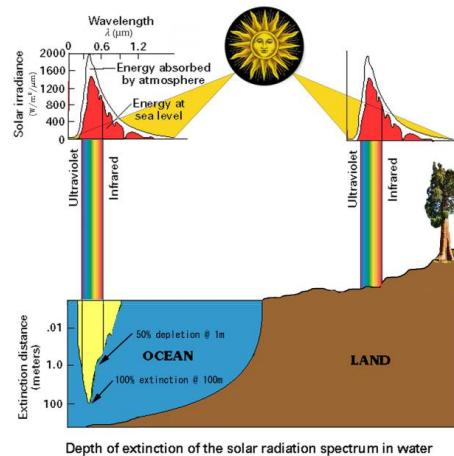
854



854

855 **Figure 16.** The moon, air, H₂O and soil (from Blakemore 2015); topsoil previously estimated as ~4,000
 856 Gt of SOM humus is herein raised about four-fold to >17,800 Gt SOM, nearly equivalent to annual
 857 global rainfall; even so it still requires much more attention and conservation efforts as it is yet the
 858 most limited and most polluted of all three vital resources (topsoil, freshwater, breathable air).

859 The surface of the Earth is primarily composed of an interface between three essential
 860 components which, in order of volume and levity (antonym of density), are: air, water and soil that
 861 together support abundances of biodiversity in the reverse order. The superficial topsoil that covers
 862 all habitable surfaces of the land as a moist, living, breathing skin that manifestly has the highest
 863 density and least volume of the three but overwhelmingly supports the greatest productivity and
 864 biomass. The oceans which, despite moderate volume, are relatively depauperate. The atmosphere
 865 has the largest volume with the lowest productivity and biomass, much of it transitory: e.g. seeds,
 866 insects, spiders and other aeronauts (volant animals) including cavernicolous bats, microbes and
 867 occasional flying-fish/squid. As well as biota, there is material exchange between these elements in
 868 the soil's moisture and aeration, the silt and (low levels of) dissolved gasses in water, and the
 869 humidity and dust in the air. The Sun's incident visible spectrum energy (for photosynthesis) is
 870 depleted by about 25% in the atmosphere, the remainder reduced 50% by -1 m and completely
 871 extinguished at -100 m depth in salty seawater, whilst on land it is variously absorbed or reflected by
 872 plants, yet barely penetrates the superficial soil and litter layers which is why land plants strive to
 873 compete for light by elevation and extension with the giant *Sequoia* reaching up to 100 m skywards
 874 while its roots and symbiotic VAM fungi may extend even deeper earthwards (Figure 17).



875

876 **Figure 17.** Photosynthesis potential of flat ocean compared to undulating and verdant land (image
 877 archive.usgs.gov/archive/sites/ks.water.usgs.gov/images/studies/surface_water/solar_irradiance/ijc.f
 878 [ig1.gif](http://archive.usgs.gov/archive/sites/ks.water.usgs.gov/images/studies/surface_water/solar_irradiance/ijc.f) modified with CC permissions). Even where light is adequate, O₂, nutrients and minerals are
 879 limited in the open oceans thus limiting biomass and productivity mainly to coastal fringes.

880 Microscopic terrestrial autotrophs (e.g. photosynthetic algae, lichens, Cyanobacteria or
 881 Cyanophyta) also coat and inhabit the convoluted superficial and interstitial surface rock, soil and
 882 sand layers in biofilm or biocrust with an often unquantified contribution to productivity on land at
 883 smaller scales.

884 **3.12. NPP**

885 The topsoil issue also relates to total net primary productivity (NPP) with land's contribution
 886 currently put at somewhere around 45–68%, yet with correct terrain/relief doubling this would be
 887 increased possibly by a factor of two (or maybe much more?) to give over 270 Gt C land productivity.
 888 This represents productivity ratio of soil : sea as at least 4 : 1 or 81 vs. 19% (Table 11).
 889

890 **Table 11.** Summary of historical and NPP data presented above with speculated new totals.

NPP Totals for 15 Gha land by authors	Rate land C g/m ² /yr	Rate sea C g/m ² /yr	Total land C Gt/yr	Total sea C Gt/yr	TOTAL NPP Gt C	% land	% sea
Duursma & Boisson 1994	144	72	21.6	25.9	48	45	55
Whitman et al. 1989	-	-	48	51	99	48	52
Stiling (1996)	773	152	115	55	170	68	32
UNEP (2002)	-	-	56.4	48.5	105	54	46
Campbell (2008) recalc.	678.9	138.5	110.3	54.8	165	67	33
NASA (2011)	-	-	93	-	-	-	-
For ~30 Gha land	725.95*	145.25*	218	52	270	81%	19%
For ~60 Gha land	725.95*	145.25*	436	52	488	89%	11%

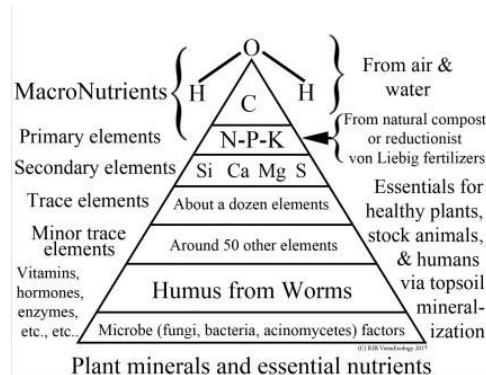
891

892 *Land and sea rates are based upon the estimated averages of Stiling (1996) and of Campbell (2008)
 893 who also included a separate 2% of freshwater productivity, now diminished by land increase).
 [Omitted data is from Field *et al.* (1998) as their calculations differ by excluding iced areas].

894 This table shows NPP per annum has apparently been doubled from 48 Gt to 99 Gt, then up to
 895 170 Gt. Each time with more refinement for the land contribution. The current study continues this
 896 trajectory to yield a total value around 270 Gt/yr (81% from 30 Gha land), albeit such conclusion
 897 requires practical confirmation on and in the ground. A further possibility is that consideration of
 898 finer soil detail (to 60 Gha) allows greater increase (to around 488 Gt C/yr).

899 Pertinent to this are calculations of land productivity per unit area from ecological quadrats that
 900 may need to be revised upwards, by ~1–5% or more, to account for terrain slope/relief (Appendix A).
 901 This too applies to earthworm surveys, conventionally tied to a flat 1 m² metric, these too may require
 902 1–5% increase but this is minor to their doubling for more refined land surface areas.

903 Getting to the crux of the Net Primary Productivity (NPP) issue, a recent report stated that: "At
 904 a certainty level of 75 %, soil C mass will not change if CO₂-induced increase of NPP is limited by nutrients."
 905 (Köchy et al. 2015.). The present paper increases soil C mass by increasing soil area/volume whereas,
 906 to the conventional, but problematical, agrichemical advocates this certainty statement would imply
 907 that even more synthetic Nitrogen and other chemicals need to be added to soils. To agroecology
 908 aficionados, the same statement implies a need to recycle all organic wastes back to the soil to "close
 909 the circle", preferably with rapid and beneficial vermicomposting, in order to fulfil what Sir Albert
 910 Howard (1945) called the Law of Return. Spontaneous generation has long been debunked and,
 911 similarly, it is not possible for any higher organism to exist without tangible resources as alluded to
 912 above: *viz.* gasses, sunlight, nutrients and habitat. Conventionally, soil nutrients are only considered
 913 in terms of simplistic chemicals N-P-K, whereas the proper plant requirements are complex and
 914 mainly carbon based, as shown in Permaculture's nutrient-pyramid charted below (Figure 18).



915

916 **Figure 18.** Plant nutrient pyramid (from Blakemore 2018c - <https://vermecology.wordpress.com>);
 917 Carbon in plants and soil is by far the most important element; atmospheric N₂ is used by nitrogen-
 918 fixing microbes and is also released by weathering of soils, the rates of which are substantially
 919 underestimated without terrain or relief.

920 The context of this recycling is that approximately 50% of global soils are managed, often
 921 deleteriously, on chemical farms, sown pastures and regrowth forests (Scharlemann et al. 2014). There
 922 is great potential to restore and to properly manage soils to their full potential also to reclaim the arid
 923 and semi-desert land using Permaculture methods (Mollison, 1988).

924 *3.13. Oceans and Space Diversions and Distractions to the Problems on Earth*

925 Copley (2017) reveals that the entire ocean floor has now been mapped to a maximum resolution
 926 of around 5 km and that: "NASA's Magellan spacecraft mapped 98% of the surface of Venus to a resolution
 927 of around 100 metres. The entire Martian surface has also been mapped at that resolution and just over 60% of

928 *the Red Planet has now been mapped at around 20m resolution. Meanwhile, selenographers have mapped all of*
929 *the lunar surface at around 100 metre resolution and now even at seven metre resolution.*" For Earth, global
930 data is available from the 2000 Shuttle Radar Topography Mission (SRTM) and ASTER Global Digital
931 Elevation Model (<https://asterweb.jpl.nasa.gov/>) with a 1 arc-second, or about 30-metres sampling
932 and some datasets have trees and other non-terrain features removed. But where *is* the compiled data
933 for the earth beneath our feet?

934 For bathymetry, a surface of 36.066 Gha has a seabed at 2–20-km resolution of 36.138 Gha
935 (Costello *et al.* 2010: tab. 1). They claim this is important as it somehow relates to ocean fisheries that,
936 nevertheless, supply <0.5% of human food (the other 0.5% mainly from freshwater aquaculture – UN-
937 FAO 2016). Regardless, only the surface of the ocean is oxygenated and exposed to sunlight thus
938 bathymetry is a completely irrelevant diversion, as are other planets' topographies, for calculations
939 of primary productivity and biota here on Earth upon which oceanographers and astronomers
940 entirely depend for their survival, as does everyone else. Moreover, marine scientists are unequivocal
941 that the ocean surface does not include the seafloor as they universally quote its surface area as 36
942 Gha, *i.e.*, the flat interface between the water, the air and the coastline abutment, even allowing them
943 an (ever increasing) high water mark.

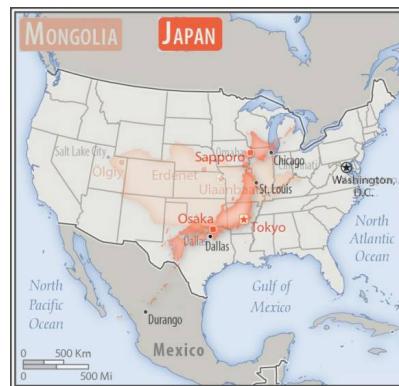
944 The latest \$10+ billion space telescope (<https://jwst.nasa.gov/about.html>) aiming yet again to
945 seek "life on planets like Earth" seems a much lower priority compared to the rapidly declining life on
946 planet Earth of which we yet know but a fraction. The same amount of funding could seed urgently
947 needed Soil Ecology Institutes on each Continent. Similarly, submarine surveys of deep-sea
948 hydrothermal vents costing \$ millions to find just a few new species, that will still be there tomorrow,
949 while essential soil species are being lost to erosion daily. Basic equipment for soil survey is a spade.
950 How justifiable is it to dabble in space or deep oceans when we don't yet know how many earthworm
951 species exist on the eponymous Earth, barely nothing of their ecology or conservation status, and
952 even less of their symbiotic/parasitic co-evolutionaries? When the latest report (IPCC 2018) gives us
953 just 12 years to act in order to prevent catastrophic change, studies of deep space or the abyss seem
954 irrational, inessential and unjustifiable funding choices that misdirect talent and resources from key,
955 critical issues emanating from and solvable only in the solid ground here and now on Earth.

956 3.14. Worked Example for Samos Island and the Land of the State of Japan

957 Aristarchus of Samos is credited with the first concept of a spherical Earth revolving around the
958 Sun, an idea later supported by Aristotle on empirical grounds. Appropriately fitting is to attempt to
959 define the topography of Aristarchus's and Pythagoras's island of Samos with its central volcanic
960 peak, Vigla, at 1,434 m. Said to have an area of 477.4 km² which, if circular would give the island a
961 radius of 12.33 km. Thus a crude approximation using Pythagorean hypotenuse as 12.41 km (= new
962 radius) gives a new surface area 483.8 km² which is only about 1.3 % larger at the km scale. But
963 allowing for topographic undulations at the one metre or less scale increasing area by 50% totals 716.1
964 km² that may itself be doubled for fractal tortuosity at cm scale to about 1,432.2 km² or 200% increase
965 over original. If hypotenuse and/or radius is increased 50% to allow for undulating curvatures (*i.e.*,
966 to 18.5), then area is 1,075 km² which if doubled for relief to 2,150 km² is substantially (350%) larger.

967 For Japan, Nunn & Puga (2012) give its flat land area as 36,450,000 ha (0.0365 Gha excluding
968 lakes, *e.g.* Biwako) and average slope of 6.275% (3.59°). If the flat area were considered a circle with
969 base diameter 6,812 units its hypotenuse of 6,850 differs by ~0.6% or about 41 units giving a proper

970 diameter of 6,853 and a new area of 36,885,132 ha. This extra 435,132 ha (4,351 km²), which is the least
971 possible, is only a modest 1.2% extra but increase in surface area is likely closer to 400% with finer
972 resolution. From the worked practical examples above, its hilly terrain allows 21.25% extra land (at
973 least) and, because soil occupies most of the land, then by 94% tortuosity and then again by 108.2%
974 relief. This gives a practical area of (0.0365 x 1.2125 = 0.044 x 1.94 = 0.085 x 2.082 =) ~0.17 Gha which is
975 larger than Mongolia's flat surface area: in the realm of 0.15 Gha before its own required
976 readjustments (Figure 19).



977

978 **Figure 19.** Japan vs. Mongolia relative sizes with revised overlain on USA.

979 *3.15. Flaws in un-flattening the Earth?*

980 Possible flaws in this land surface argument are that the estimation of quadrupled land area may
981 be excessive, or it may be an underestimation depending upon what scale is chosen. The question is
982 why nobody knows this basic data about Earth? Certainly, the present IPCC/NASA/NOAA values
983 are wrong. Other criticisms may be that Landsat and other satellites if set to measure
984 perpendicular/planimetric values make terrain less relevant. And, because land productivity
985 calculation is more difficult compared to ocean or atmosphere budgets, the IPCC (2014) estimates soil
986 carbon contributions based upon emissions minus atmospheric and oceanic uptake. The residual
987 difference is reasonably ascribed to the land which appears a quite valid method and the "missing
988 sink" discrepancy easily attributed to underestimation of the sub-soil components. Carbon sink
989 calculations when ascribed to biomes may also be artificial due to boundary differences affecting
990 relative % (which may be independent of topography). For example, FAO (2005) have grasslands
991 covering 40.5% of land comprised of woody savannah/savannah (13.8%), open/closed shrub (12.7%),
992 non-woody grassland (8.5%) and tundra (5.7%); whereas other systems separate these biomes. Other
993 calculations relating to carbon stored and released (either eroded or respired) from agriculture,
994 forestry and other land-use changes, primary productivity and biodiversity studies, however,
995 certainly do need to employ topography details down to cm or mm scale for true tallies.

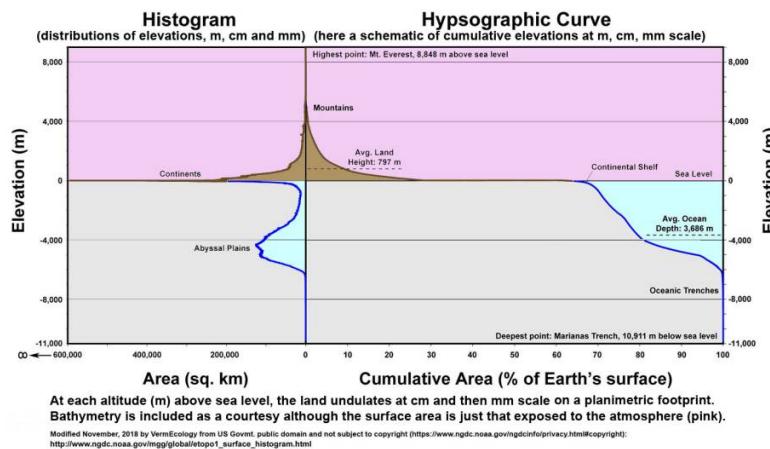
996 Regarding soil biomass, as carbon values are drawn from loss-on-ignition (LOI), or Walkley-
997 Black they may include much of the microbiota (although certainly not the larger megadrile
998 earthworms nor sieved roots), whereas microbial measurements often take smaller samples and
999 either extract DNA or use plate cultures to estimate biomass and diversity. Thus the intermesh of
1000 chemical and biotic factors may unintentionally overlap to overstate total carbon in SOM humus.

1001 Conversely, when carbon or microbes, or any other organisms, are ascribed to "flat-Earth"
1002 biomes then the calculations are invariably and undeniably wide underestimations of both soil depth
1003 and of probable land surface area they occupy in reality or potentially.

1004 **4. Conclusions**

1005 "We know more about the movement of celestial bodies than about the soil underfoot" – da Vinci (ca. 1500s).

1006 True surface area of uneven land on Earth is conclusively raised above the conventional 15 Gha.
 1007 New estimates vary from 52.8–75 Gha with a reasoned arbitrary value set at 64 Gha. Soil organic
 1008 carbon (SOC) is consequently also upped to ~9,000 Gt, SOM to >18,000 Gt and global biomass,
 1009 biodiversity and productivity also substantially raised on the land. Soil bulk density data are most
 1010 compelling as anyone may check for themselves since, if the figures differ, then either the BD
 1011 averages are inexact and the SOC data mistaken or, as suggested here, the undulating topography is
 1012 overlooked. As land is one of our three basic biospheric arcs of survival it is surely important to
 1013 attempt definition of its fundamental metrics and, most crucially, the amount of vital organic topsoil
 1014 remaining thereupon. It seems classical wisdom and prescient warnings from Plato, Aristotle, da
 1015 Vinci and Darwin need to be revisited. The Earth's inclusive terrain model – with most life in the top
 1016 10 cm of its thin brown line of soil – is summarized in the following schematic (Figure 20).



1017

1018 **Figure 20.** New view of Earth's meaningful surface area (modified from
 1019 www.ngdc.noaa.gov/mgg/global/etopo1_surface_histogram.html).

1020 Geomorphologists study rough land surfaces since smooth or flat patches, apart from bodies of
 1021 water, are extremely rare on Earth. Geodesy is concerned with precise determination of the Earth's
 1022 surfaces (called bathymetry in the sea but considered of lesser import due to deficits in oxygen,
 1023 sunlight, nutrients and, consequently, biota). These experts are called upon to provide the correct
 1024 eco-geodesy values for calculating the true soil surface areas and of the total Life on Earth.

1025 **Supplementary Materials:** Excel data files and a supplementary BD text file are attached.1026 **Funding:** This research received no external funding.

1027 **Acknowledgments:** Anonymous referees and journal editors are thanked for their constructive comments.
 1028 Thank are extended to several authors of recent papers who, while unable to provide actual information on
 1029 global topography, did provide some useful direction (pers. comms.): e.g. Dr Fiachra O'Loughlin (2016), Dr
 1030 Christian Hirt author of other papers on SRTM (2015), his colleague Prof. Michael Kuhn, Dr T. Tadano (2016),
 1031 Dr Y.S. Hayakawa (2008), and Dr Kenneth Falconer at St Andrews University in Scotland, UK.

1032 **Conflicts of Interest:** The author declares no conflict of interest.1033 **Appendix A**

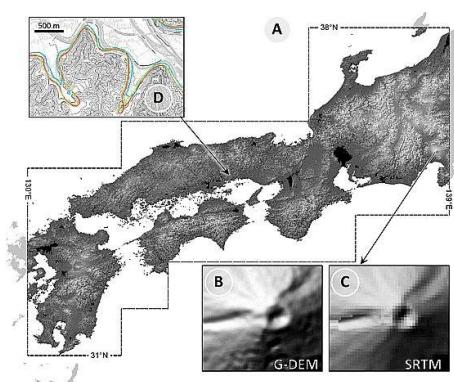
1034 **Sampling Quadrat Slope Errors.** Regarding ecological quadrat surveys, data from these are almost
 1035 always considered or presented from a planimetric viewpoint: on a flat area basis, yet truly flat land
 1036 is rare. Standard quadrats have a manageable proportion of a 100 cm square with area of 10,000 cm²
 1037 (= 1 m²) but if used on a 10° slope the isometric base length would be 98.5 cm giving an area (98.5 x
 1038 100) of 9,850 cm² or -1.50% (or an area increased by 1.52–2% as with the triangle). A 20° slope with
 1039 100 cm hypotenuse has sides of 94 cm (area 9,400 cm²) which is -6.0% less (or the area is increased by
 1040 at least 6.38%). If the quadrat is laid obliquely with a corner upslope then the true area would be
 1041 decreased further by varying amounts possibly exceeding -55% (see Figure above).

1042 A survey's result with biodiversity or productivity from these quadrats are projected onto a
 1043 lesser flat surface area and are thus variably reduced, being correct only when true topography is
 1044 factored in. The obvious solution would be to ensure the quadrat is a perpendicular projection for
 1045 any measurements. However, in most cases only planimetric results are presented and analysed
 1046 which, since most land has both slope and undulation, are certainly underestimations. Aquatic
 1047 calculations are unbiased being both or either flat surfaced or water volume-based (bathymetry is
 1048 discussed later).

1049 Albeit the required orthometric projections are complex, attempts at resolution of topography
 1050 are, for example, in an ecological study noted by Jenness (2004): "Bowden *et al.* (2003) found that ratio
 1051 estimators of Mexican spotted owl (*Strix occidentalis lucida*) population size were more precise using a version
 1052 of this surface area ratio than with planimetric area". Of incidental note is that size of quadrat or sampling
 1053 tool depends upon size of the organism or feature sought; often microfaunal surveys (e.g. for
 1054 superficial Collembola or mites and interstitial nematodes) use 1–5 cm, samples yet erroneously
 1055 report zero earthworms due to scale incongruity.

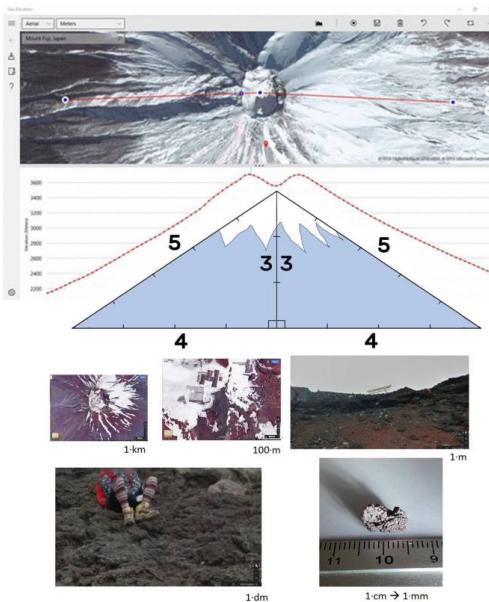
1056

1057 **Mt Fuji Example.** As a simple example of terrain: Mt Fuji that is visible from Tokyo/Yokohama is 3.8
 1058 km high with mean basal diameter of 38 km (radius = 19 km) and circumference of 123 km giving it
 1059 a flat NASA 'footprint' of ca. 1,134 km². Calculated as two opposed right-angled triangles, with
 1060 hypotenuses of $19.37 \times 2 = 38.74$ km is about 1.95%. If a perfectly smooth cone, this gives a lateral
 1061 surface skin area of 1,156 km² or 1.9% larger (as with triangles), yet allowing for its curve and taking
 1062 the height as the sagitta and the diameter as the chord length, then the inverse arc length area is about
 1063 2.5% larger with surface area of about 1,162 km². Secondary undulations and micro-terrain at
 1064 increasing scale could reasonably be assumed to double this to ~2,324 km² and again to 4,648 km², or
 1065 by about +302%. At higher scale especially, Mt Fuji comprises scoria riddled with irregular pore
 1066 spaces thus approaching infinite surface area; just as human lungs are said to have an internal surface
 1067 area equivalent to a tennis court (Figures A1-2).



1068

1069
1070
1071 **Figure A1.** Satellite imagery of western Japan with Mt Fuji example (from Hayakawa *et al.*, 2008: fig.
1B-C with permissible repost - <https://publications.agu.org/author-resource-center/usage-permissions/>), but yet no total TMA surface area estimations are provided.

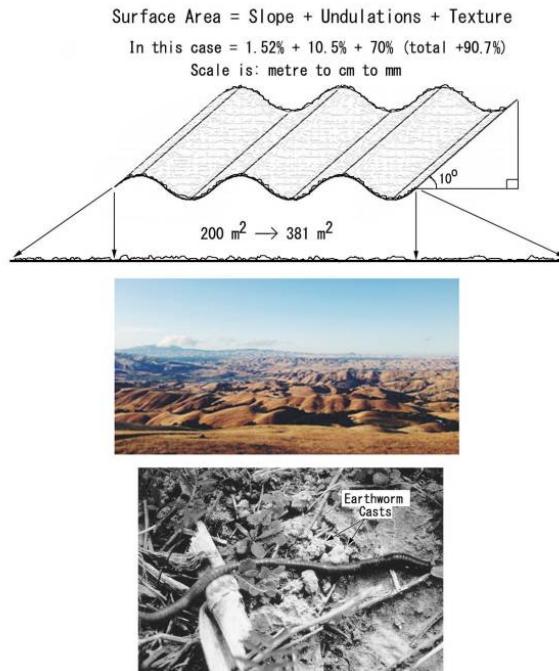


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1076 **Figure A2.** Profile of Mt Fuji with ~12.5% greater relief than linear distance translating as ~12.5%
greater surface area, itself multiplied at finer resolution; if same scale as the right triangles it would
be +25% (topography modified from www.microsoft.com/en-us/store/p/geo-elevation-map-elevation-chart-creator/9nblggh5wn5j, GoogleEarth, and photography by the author).

1077 As Japan itself is about 73% mountainous we may envisage a topography much above the
1078 reported flat surface area of just 378,000 km² (0.0378 Gha) being 2–4 times larger (e.g., land area
1079 increased to 0.0756–0.1512 Gha), as is estimated in Results section of main paper text above.
1080

1081 **Paint Analogy.** Perhaps the best analogy for the soil surface area is from a paint manufacturer's
1082 estimate (<http://www.resene.co.nz/archspec/datasheets/Section1-Surface-Areas.pdf> Sept. 2018) that a
1083 200 m² corrugated sheet has 10.5% larger surface area, and that Anaglypta or Stucco textures (*i.e.*,
1084 bumpy like an actual soil surface) require 40–100% (median 70%) extra paint to that of the base area.
1085 Moreover, if this corrugated sheet is on a slope then the planimetric surface area (e.g. its
1086 perpendicularly vertical projected shadow) is also foreshortened thereby effectively increasing the
1087 actual area correspondingly. For example, if the sheet was 2 × 10 m (200 m²) on a 10° slope with
1088 hypotenuse of 10 m its projected isometric base is 98.5 m or about -1.5% less (or the sheet appears
1089 +1.52% greater and, if the base was 10 m then the hypotenuse is 2% longer) which is an important
1090 consideration for all quadrat surveys too, as already noted. In scale order, the slope (m) gives +1.52%
1091 or 203 m², undulations (dm or cm) × 10.5% (= 224 m²) and texture relief (cm or mm) × 70% = 381 m²
1092 total surface area or an extra +90.67%. Reversing the order (70% × 1.5% × 1.52%), although improper,
1093 has negligible difference in outcome in this case – coming to about the same as +90.71% (Figure A3).



Landscape is more convoluted and the soil surface more complex

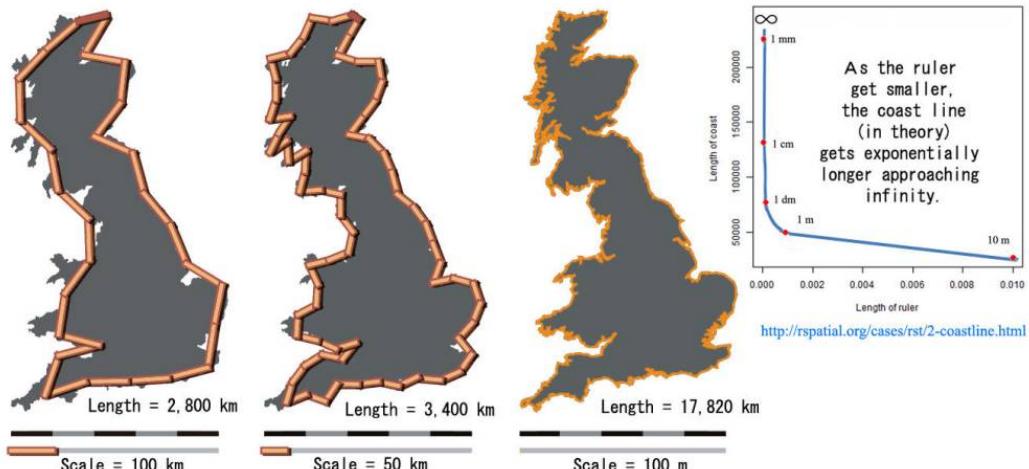
1094

1095 **Figure A3.** A rugose corrugated-sheet/paint analogy for terrain; with photo of irregular, undulating
 1096 landscape in Colorado River region of USA that is manifestly not flat (from
 1097 <https://sustainabilitybox.com/colorado-river-concerns-desert-agriculture-water-experts-says/>) and
 1098 soil surface complexity (from Cornell university Soil Ecology website
 1099 www.css.cornell.edu/courses/260/Soil%20Eco%202.pdf); note soil also has pits and hollows.

1100 **Kimono Analogy.** A slightly less transferable analogy than paint is for clothes covering a lady, "as
 1101 with a mantle". Her body's life-sized silhouette shadow cast on a flat wall will be a lesser area than the
 1102 mommes of kimono silk, with the raised surface textures of shibori further increasing the material
 1103 required (e.g. www.thekubotacollection.com/en/collection-highlights/ohn-4).

1104

1105 **Coastline Paradox Analogy.** Another 2-D corollary to the 3-D dilemma is the "Coastline Paradox" or
 1106 Richardson effect (https://en.wikipedia.org/wiki/Coastline_paradox) whereby decreasing scale
 1107 increases length. An example is Great Britain's coastline that multiplies with finer resolution of
 1108 observation: from 2,800 km (at a 100 km scale), to 3,400 km or +50% (at 50 km) scale. From UK's
 1109 Ordnance Survey (OS) at 1:10,000 mapping scale where 1 cm on a map = 100 m and measuring to
 1110 mean high water mark (England & Wales) and/or mean high water Springs mark (Scotland), the coast
 1111 is 17,820 km – or a six fold increase (536%). It may yet reach 28,000 km in its Hausforff measure
 1112 (https://en.wikipedia.org/wiki/List_of_countries_by_length_of_coastline). At theoretical values it
 1113 increases exponentially from 48,000 km at 10 m scale towards infinity as the length of ruler
 1114 approaches zero (Figure A4).



1115

1116 **Figure A4.** Great Britain's coastline paradox (from Wikipedia commons and other cited sources, with
 1117 modifications); UK's land area may be similarly increased at finer scales of measurement from current
 1118 flat 0.024 Gha to topographically expected >0.096 Gha.

1119 Richardson's fellow mathematician, Benoit Mandelbrot (1983), further investigated this fractal
 1120 phenomenon which, as with the soil surface, is by definition a curve whose complexity changes with
 1121 measurement scale. Thus a 2–4 fold increase is perhaps entirely reasonable for 3-D landscape
 1122 estimates that have fractal complexities. Interestingly, the coastline of the whole of the UK's islands
 1123 OS figures as 31,368 km, whereas CIA Factbook has less than half this at just 12,429 km but accepts
 1124 that UK's terrain is mostly rugged hills and low mountains with level to rolling hills. Both the CIA
 1125 and United Nations have UK's total (flat) land surface area as 241,930 km² or 0.024 Gha as part of a
 1126 flat Earth with 14.89 Gha land, whereas UK's true terrain and relief may actually amount to >0.096
 1127 Gha, a fourfold increase, from the current study.

1128 The CIA factbook (www.cia.gov/library/publications/the-world-factbook/geos/xx.html) gives
 1129 Earth's flat land area as 149 million sq km (Africa occupies 54% of this) and the global coastline is
 1130 quoted as "1,162,306 km" (1.16 million km) but with no scale of observation. If such an area of land
 1131 was a square the length of side would be 12.2 million km which $\times 4 = 48.8$ million km; if circular the
 1132 area would have a circumference of 43.26 million km; thus their estimate of coastline of 1.16 million
 1133 km is at an unrealistically large scale (perhaps >500 km intervals) and is out about 50 times. The land's
 1134 boundary then is an unknown metric. Prior Pangaea or Rodinia landmasses are often conceptually
 1135 represented as more circular, certainly in Nature such as the coastal boundaries there are few straight
 1136 lines and many subtle irregularities.

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