

Article

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

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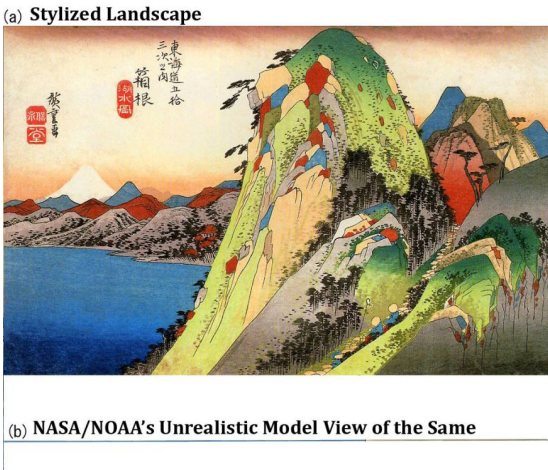
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**Abstract:** Earth's land surface area is raised from conventionally flat 15 to 64 Gha to account for hilly undulation and soil relief detail. Three main aspects are: topography, rugosity/tortuosity and micro-relief/porosity of vegetation-free ground.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

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

## 1. Introduction

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



**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.

1.1. Land’s surface area

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](http://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).

**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

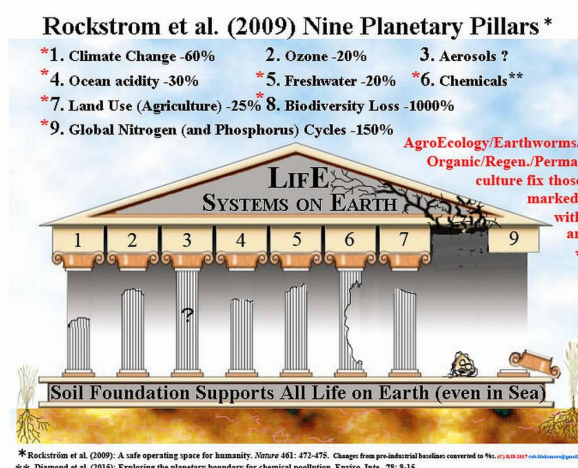
\*FAO data from Nunn & Puga (2008: appendix) has ~15 Gha planimetric land including hot or cold deserts and water bodies (temporary freshwater inundations, paddy, bogs, marshes, or swamps may

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

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

## 1.2. Global Triage

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



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

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

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

1.3 Vital Global Resources

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

**Table 2.** Primary Productivity (P.P.) in terms of organic C and O<sub>2</sub> (Duursma & Boisson 1994: tab. 2).

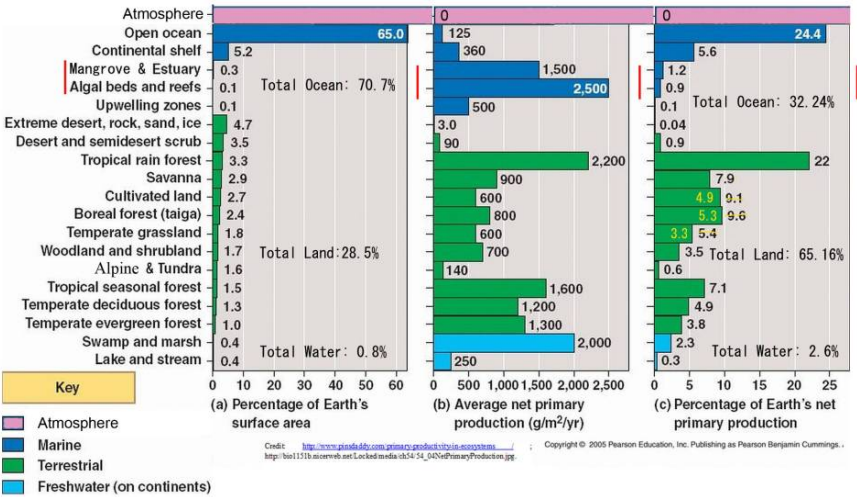
P.P.	Area Gha	Org-C g/m <sup>2</sup> /yr	Total Org-C Gt/yr	O <sub>2</sub> g/m <sup>2</sup> /yr	Total O <sub>2</sub> Gt/yr
Land	15*	144	21.6 (46%)*	384	57.6 (44%)
Ocean	36	72	25.9 (54%)	206	74.3 (56%)
<b>TOTAL</b>	<b>51</b>		<b>47.5 (100%)</b>		<b>131.9 (100%)**</b>

\*Land area is contested in the present work so its productivity may be at least doubled. \*\*It is also nonsense to claim “oceans provide every second breath of air” because a massive atmospheric O<sub>2</sub> reserve is 1.2 million Gt thus 131.9 Gt annual photosynthetic contribution from soil and sea combined is just 0.01% per year and turnover time for all O<sub>2</sub> in the order of 10,000 yrs – a literal ‘drop in the ocean’. Duursma & Boisson (1994) further state that oceans contain just 0.22% of global living biomass.

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



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

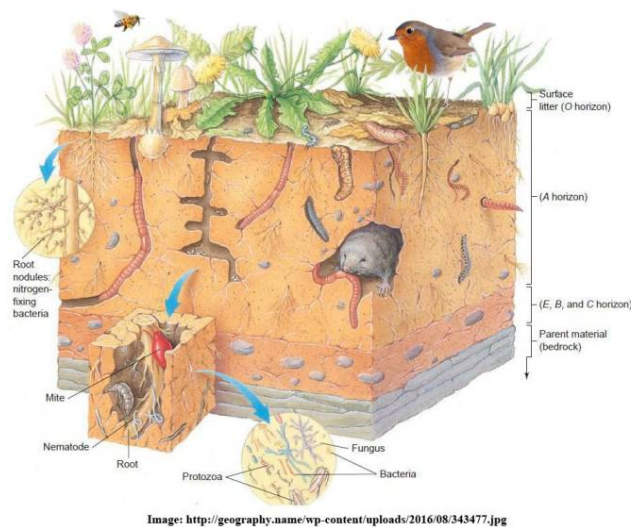


**Figure 3.** Contributions of (flat) biomes to NPP (corrected in yellow); despite contrary claims, mangroves or coral reef (in red) are of minimal importance, ~2% overall. [After Campbell, N.A. & Reece, J.B. (2005:fig. 54.4a-c) from “Stiling (1996), *Ecology: Theories and Applications* (Prentice Hall)”).]

Primary productivity that provides for all Life on Earth operates at the biological scale of a leaf and seed or of an earthworm’s burrows and castings, both around the centimetre to millimetre level. Average leaf size reportedly ranges from 0.011 to about 39.5 cm<sup>2</sup> (Falser & Westerby 2003), an earthworm’s burrow is about 0.1–1.0 cm diameter (Lee 1985). However, a true range of total topographical topsoil that actually supports land plants and hosts earthworms is wanting.

1.3.1. Biodiversity and Biomass

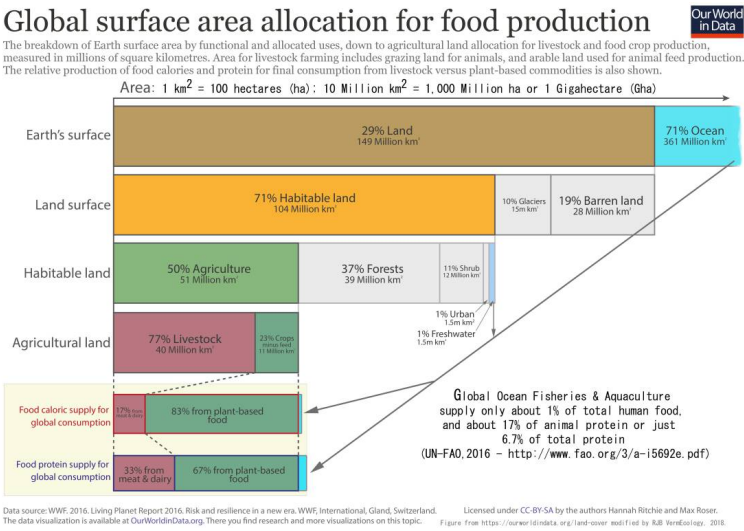
The majority of deep carbon in soils is stored as SOM-humus composed of decaying plants and both living and dead (or dormant) animals, fungi and microbes. One cubic metre of soil may support ~200,000 arthropods, ~2,000 earthworms, countless other larger or lesser organisms plus up to 112 km m<sup>-2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



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

1.3.2. Neglected Soils and Earthworms

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



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

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

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

#### 1.4. Aims of this study

Despite depletion, the soil is yet key for biota, for regulation of atmospheric gases (e.g., CO<sub>2</sub>, N<sub>2</sub>O, CH<sub>4</sub>) – as shown in NASA's (2011) figures – it underpins primary production plus its humus is the interface of adsorption/retention/rehabilitation of pollutants such as heavy metals and pesticides. Due to this dependency and urgency one would think that the status of soil is well worked out as a major concern. In fact, the opposite is true and more seems known about the relatively unproductive and unpopulated oceans or the status of inert dirt on other planets than of the living topsoil on habitable Earth. Inexplicably, the less critical spheres of air, water and space are most exquisitely plotted and their research is well supported.

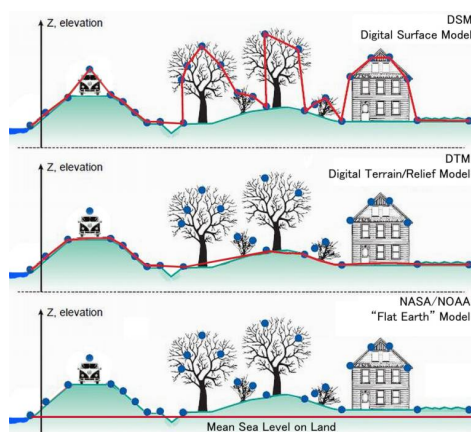
The present study aims to provide some initial direction to help redress this unfathomable imbalance of an abysmal lack of soil ecology and lack of knowledge or information of the terrestrial biome. It does not provide a definitive answer to the total surface area of land nor volume of topsoil: rather,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

## 2. Materials and Methods

### 2.1. Theoretical Basis: Digital Elevation Models (DEMs)

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

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



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

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

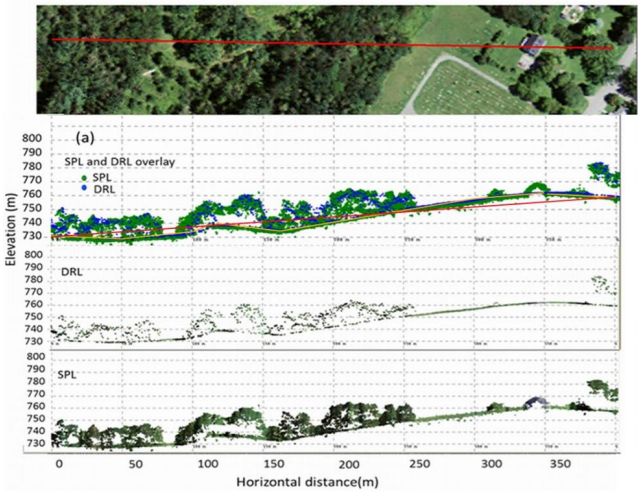
## 2.2. Satellites and LiDAR (laser *Light Detection And Ranging*)

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

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

Swatantran *et al.* (2015: fig. 4) provide a methodology but give no practical example of the surface area to horizontal area. They mapped the entirety of Garrett County, Maryland, USA, covering a flat 1,700 km<sup>2</sup> area but enquiries of the authors for terrain totals were to-date unanswered, while their demonstrable summary image is shown in the figure below (Figure 7).



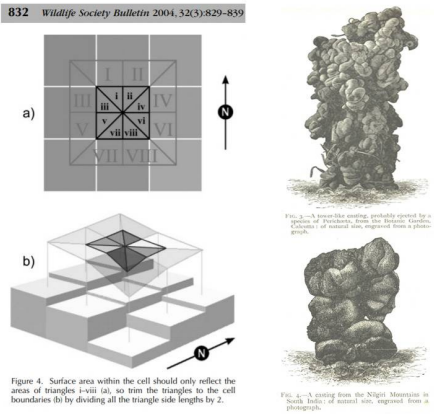


**Figure 7.** Real-time photon scale LiDAR scan (modified from CC of Swatantran *et al.* 2016: fig. 4) .

2.3. DEM Errors and Straight Line Underestimations

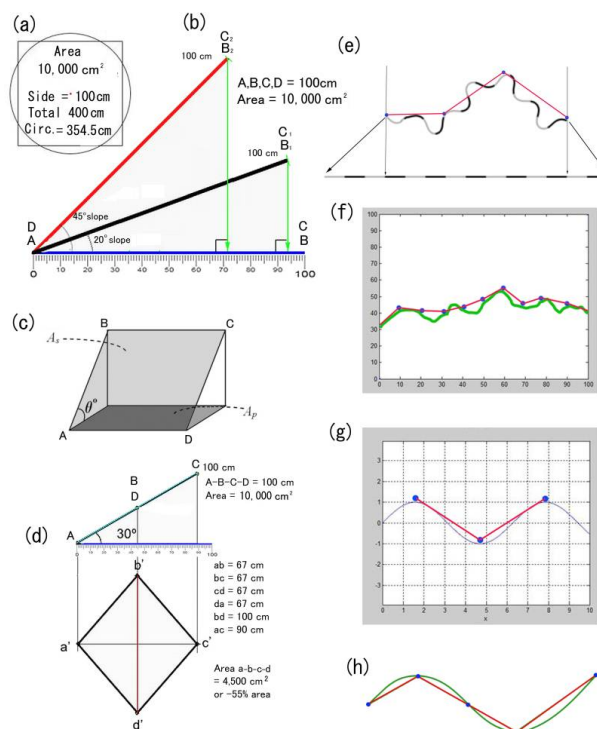
For macro terrain a need is to find 3-D surface area to 2-D planimetric area ratio of a mapped topographic surface. Jenness (2004) says: “There are a variety of methods in the literature for measuring terrain irregularity. Hobson (1972) described some early computational methods for estimating surface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

Jenness (2004) mapped an area of USA of 54,850 km<sup>2</sup>, but seem to not provide a 3-D area for this. Part of his method of computation is demonstrated in the figure below, in comparison to actual biotic elements such as worm casts (Figure 8).



**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.

A 3-D Tortuosity index is  $T_i = TSA/TMA$  where TSA=Total Surface Area, TMA=Total Map Area at specified scale (subscript i) but often only linear profile ratios are made of surface relief by a flat Euclidean line ( $L1/L0$ ) thus no account is taken of curved or irregular arcs. A major problem with slope approximations, depending upon the algorithm used, is that ascendancies may be cancelled by declines, and *vice versa*, plus the slope aspects are random and irregular with regards to any fixed compass points adding yet more complexity. In other words, slope summaries are likely to be considerable underestimations at the larger scale, and natural curves and convoluted distortions of detail features are also unaccounted for by models. If mean model ratio value is 1.6–2.0 that means increases of 60–100% are to be expected with median value 80%. Much more accurate are actual on-the-ground survey data compilations. Microrelief may be further overlooked as a constant error in most DEMs. Some of the concepts proposed and applied herein are illustrated below (Figure 9).



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

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

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

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

#### 2.4. Appropriate Scales

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

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

#### 2.5. Practical and Theoretical Determination of New Land Areas

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

terrain is plotted, the first country to have this data at 1 arc-sec detail (ca. 31-m), but efforts to obtain a summary from published reports or direct enquiries thus far are unanswered (<https://data.gov.au/dataset/9a9284b6-eb45-4a13-97d0-91bf25f1187b>; [www.ga.gov.au/metadata-gateway/metadata/record/gcat\\_72759](http://www.ga.gov.au/metadata-gateway/metadata/record/gcat_72759)).

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

Throughout, SOC and SOM = Soil Organic Carbon and Soil Organic Matter that have a ratio of 1 : 2 (Pribyl 2010). A dash is used to indicate scale of observation in land surveys, e.g. 1-m, 5-cm, etc. One km<sup>2</sup> = 100 hectares (ha); 10 Million km<sup>2</sup> = 1,000 Million ha or 1 Gigahectare (Gha).

### 3. Results and Discussion

#### 3.1. Global Terrain Recalculation

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

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

##### 3.1.1. Macro: Terrain

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



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

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

Author	Scale m	Slope °	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	<b>0.9365**</b>	0	0
% Diff. 1 <i>vs.</i> 1,000-m		>240%	~240%	2.0%	>1,074%	804%

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

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

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

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

2.8) at 100-m scale, more than double that of 130 km<sup>2</sup> (30%) at the 500-m scale, while at the 1-km scale the surface area appears to be only about 110 km<sup>2</sup> (or just 10% larger).

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

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

### 3.1.2. Meso: Tortuosity and Soil Roughness or Rugosity

The meso scale relates to an important measure of insolation defined as solar irradiance with energy measured in watt-hours per square metre (Wh/m<sup>2</sup>) or in the Langley which is 1 calorie per square centimetre (= 41,840 J/m<sup>2</sup>). These are both defined for horizontal area values and the latter cm<sup>2</sup> scale is approximately the same size as an earthworm burrow or surface cast. This is an appropriate level of observation for measuring basic ecological interactions locally and then extrapolating to a global value (as is routinely done by NASA, UN, FAO, IPCC, *etc.*). See also ([www.nature.com/scitable/knowledge/library/the-soil-biota-84078125](http://www.nature.com/scitable/knowledge/library/the-soil-biota-84078125)).

From the foregoing, it seems that tortuosity is strongly influenced by the scale factor: the more intense, the higher the tortuosity index (T value). Indeed a study in Canada by Martin *et al.* (2008) shows a fourfold increase in bare earth tortuosity only when resolution was reduced to less than 10-cm starting from one metre scale. Martin (2008: fig. 5, tab. 1) show T<sub>B</sub> value of 16 based upon a T<sub>A</sub> Tortuosity index of 1.2 from a TSA of 240 m<sup>2</sup> and TMA of 200 m<sup>2</sup>, *i.e.*, 20% greater surface area for bare soil at their 0.75-cm scale. However, it appears this study, as with several others, did not adequately consider slope foreshortening which for a straight hypotenuse of about 20 m and stated angle of 18 degrees gives a baseline of 19 m or 5% lesser base length. Unrealistically assuming the slope is smooth and constant for its width, this then gives a simple Tortuosity Index of at least 240/190 = 1.26 (+26%), which is 5% above their calculation. Note that in this study [Martin 2008: fig. 5(a)], the vegetated rather than bare soil hillslope had tortuosity index of about 1.5 or at least a twice as high surface area as the bare earth value.

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

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

### 3.1.3. Micro: Biodiversity, Productivity and Respiration

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

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

An online accessible but possibly unpublished Canadian thesis has cultivated soil surface area up to almost double the flat area (1.9 m/m<sup>2</sup>) with a mean value of laser roughness at the less than 1-mm scale of 1.6 (+60%) (Koiter 2008: tabs. 2.3, 2.6, 2.7).

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

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

At the microporous scale, soil organic matter (SOM) and its colloids are reported to have adsorbic surface area for gaseous exchange of CO<sub>2</sub> of between 94–174 m<sup>2</sup>g<sup>-1</sup> (de Jonge 1996: tab. 2) with a mean of 130 m<sup>2</sup>g<sup>-1</sup>. [This value of 130 m<sup>2</sup>g<sup>-1</sup> is used in calculations of humic SOM bulk densities below (and in an attached summary report)]. His paper quoted earlier studies showing SOM surface areas up to 800 m<sup>2</sup>g<sup>-1</sup>, or six times greater, and this latter value approaches that of mineral zeolite or montmorillonite (also known as bentonite) clay. However, other studies only found 1 m<sup>2</sup>g<sup>-1</sup> (Chiou *et al.* 1990). The SOM data are on an “ash free basis”, *i.e.*, just the dry, organic content of the sample is calculated even though a non-porous, inert mineral component was present in the samples. The solid phase densities average about 1.1 gcm<sup>-3</sup> (de Jonge 1996: tab. 2) and, regardless of whether from square or cylindrical measurements, the base area would be about 1 cm<sup>2</sup>. The ratio of surface area (130 m<sup>2</sup>) to flat area (1 cm<sup>2</sup>) is thus approximately (10,000 x 130 =) 1.3 million times. As soil on a “flat-Earth” occupies ~12 Gha then this would theoretically have surface area also increased by 12 x (1.3 x 10<sup>6</sup>) = 15.6 Pha. This implies that true adsorbic surface area of soil exposed to the atmosphere is almost infinitely expandable – as with the coastal paradox cited in Appendix A and as for the theoretical DTM and DSM models newly re-calculated in the section below.

3.1.5. Total Recalibration for New Land Surface Areas

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

**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

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

**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.
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	(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 Gha	3.1	3.6		
(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
<b>TOTAL (e) + Difference (d) (A)</b>				<b>52.8</b>
<b>TOTAL (f) + Difference (d) (B)</b>				<b>62.6</b>
				<b>252%</b>
				<b>x 3.5</b>
				<b>317%</b>
				<b>x 4.2</b>

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

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

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

### 3.2. Theoretical DTM Model Calculations

Jenness (2008) noted slope-aspect algorithms generated indices around 1.6–2.0 (as per Hodgson 1995) with a median 1.8. Thus from a land surface of 15 Gha, at the metre or dm scale, this may increase to 27 Gha and, as 80% supports soil, its tortuosity at the cm scale may be similarly increased 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 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 Gha barren land ( $27 \times 20\%$ ) gives a theoretical new total surface area of ~111.4 Gha which is tolerably close to the values (100 Gha) calculated above from on-the-ground field readings.

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

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

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

### 3.3. DTM and DSM Recalculation

Overlain upon the bare-earth terrain DTM is an increasing superficial DSM. An estimate of effective DSM is possible if we apply a Leaf-Area-Index (LAI). This is a dimensionless quantity that characterizes plant canopies defined as the one-sided green leaf area perpendicular to flat unit ground surface area ( $LAI = \text{leaf area} / \text{flat ground area, m}^2 / \text{m}^2$ ). LAI ranges from 0 (bare ground) to ~18 (dense forests) and a global average (from Asner *et al.* 2003) is 4.5. These authors state that “LAI is a key variable for regional and global models of biosphere-atmosphere exchanges of energy, carbon dioxide, water vapour, and other materials.” It is surely just as important to have estimates of a global DTM and DSM too. Prof. Greg Asner (pers. comm. email 20/7/2017) kindly clarified: “That estimate is the average of studies published for different vegetated ecosystems, so it does not represent the actual global land area”. Thus only soil bearing terrain is considered in the following calculations.

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

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

Subterranea (*e.g.* caves, caverns or karsts) are an additional but minor ‘surface’ area consideration, but earthworm burrows may be considerable. Burrows systems, as noted above, were found to extend for up to 888 m/m<sup>2</sup> in length (= 8,880 km ha<sup>-1</sup>) and their void volume varied tenfold from 1.3–12.0 m<sup>3</sup>/m<sup>2</sup> ground surface in the upper 1.2 m of soil during an observation period of 1.5 years (Kretschmar, 1982; Lee, 1985: 196, 208). On conventional 12 Gha flat soil this is at least 1.3 ha/ha  $\times$  12 Gha = 15.6 Gha. But on rugose soil this would be about 4 times greater, *i.e.*, at least 62.4 Gha that may vary up to 624 Gha or a 0.6 Tera-hectare volume of below-ground earthworm burrow voids! It should be noted that the study mainly represented pasture soils in France, but the samples excluded both the 0–6 cm layer of soil and also burrows <2mm in diameter (Lee, 1985: 196). Including these

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

3.4. Soil, C and a “Missing Sink” Soil Discrepancy

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

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

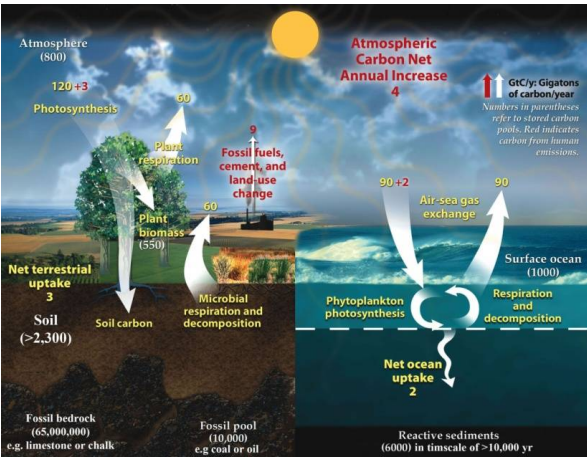
3.5. Total Soil Carbon (SOC + SOM) Recalculation of Global Carbon Budget

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

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

Greenhouse gas GHG	Potentiality (GWP)	Emission (1990) Gt	Contribution %
CO <sub>2</sub> carbon dioxide	1	26	61
CH <sub>4</sub> methane	21	0.3	15
N <sub>2</sub> 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

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



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

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

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

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



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

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

### 3.6. Bulk Density (BD) Backcheck

Support for the terrain argument is from bulk density (BD) that compels revision. Tangible subsamples are taken on the ground at fixed core sample volume with a constant planimetric area (cm<sup>2</sup> or m<sup>2</sup>) and multiplied by a biome's area, thus mass may be adjusted to comply only by adding biome area by adding biome terrain/relief.

For habitable biomes supposedly totaling 12.3 (flat) Gha, Whitman *et al.* (1998: tab. 2; Ref) gave mean soil bulk density as 1.3 gcm<sup>-3</sup> (= tm<sup>-3</sup>) and Lee (1985: 195) assumed a bulk density of 1.4 gcm<sup>-3</sup> so a reasonable mean may be 1.35 gcm<sup>-3</sup>. Total SOC to one metre recalculated (from HWSO as in attached data file) gives median values for SOC of around 1.3% and their mean soil BD is ~1.4 gcm<sup>-3</sup> (close to 1.35 gcm<sup>-3</sup>). Total conventional “flat-Earth” topsoil mass to 1 m depth would then be [(123 x 10<sup>12</sup> m<sup>3</sup>) x 1.35 tm<sup>-3</sup> = (166 x 10<sup>12</sup> t) =] 166,000 Gt topsoil and 1.3% SOC = 2,158 Gt globally, allowing that organic soils have lower BD than mineral soils.

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

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

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

Another calculation, possibly artifactual, is with prior SOC >1 m depth (Köchy *et al.* 2015) of 3,000 Gt x 2 for 6,000 Gt SOM on planimetric 12 Gha if to a sample depth of 3 m = 360,000 Gm<sup>3</sup> giving real SOM bulk density of just 0.016 tm<sup>-3</sup> or out by a factor of six for average BD of peaty SOM of

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

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

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

BD $\text{tm}^{-3}$	Area $\text{Gm}^2$	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)

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

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

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

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

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

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

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

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

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

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

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 <sub>2</sub> – C		800
<b>Biomass in + on land (plants + micro)</b>		<b>***2,000</b>
<b>Biomass in sea</b>		<b>***15</b>
<b>TOTAL</b>	<b>81,041,350</b>	<b>12,415</b>

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

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

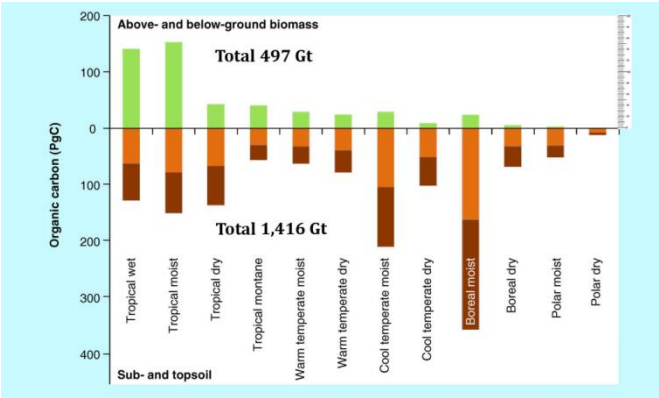
**Table 9.** Above tabulated data combined with that from Duursma & Boisson (1994: tab. 2) for total amounts of primary elements of total carbon and gaseous oxygen (with relative % proportions).

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

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

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

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



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



Taxon			Mass [Gt C = 10 <sup>15</sup> g C]	Abundance
Plants	Trees		450	10 <sup>13</sup>
Bacteria	Terrestrial deep subsurface		60	10 <sup>30</sup>
	Marine deep subsurface		7	10 <sup>29</sup>
	Soil		7	10 <sup>29</sup>
	Marine		1.3	10 <sup>29</sup>
	Total		70	10 <sup>30</sup>
Fungi			12	10 <sup>27</sup>
Archaea	Terrestrial deep subsurface		4	10 <sup>29</sup>
	Marine deep subsurface		3	10 <sup>29</sup>
	Soil		0.5	10 <sup>28</sup>
	Marine		0.3	10 <sup>28</sup>
	Total		7	10 <sup>29</sup>
Protists			4	10 <sup>27</sup>
Animals	Chordates	Fish	0.7 (0.5)	10 <sup>15</sup>
		Livestock	0.1	10 <sup>10</sup>
		Humans	0.06	10 <sup>10</sup>
		Wild mammals	0.007	
		Wild birds	0.002	10 <sup>11</sup>
	Arthropods	Terrestrial	0.2	10 <sup>18</sup>
		Marine	1	10 <sup>20</sup>
	Annelids	0.2 (0.82)	10 <sup>18</sup>	
	Molluscs	0.2	10 <sup>18</sup>	
	Cnidarians	0.1	10 <sup>16</sup>	
	Nematodes	0.02	10 <sup>21</sup>	
	Total		2 (2.42)	10 <sup>21</sup>
Viruses			0.2	10 <sup>31</sup>

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

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

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

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

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

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

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

**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%)

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

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

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

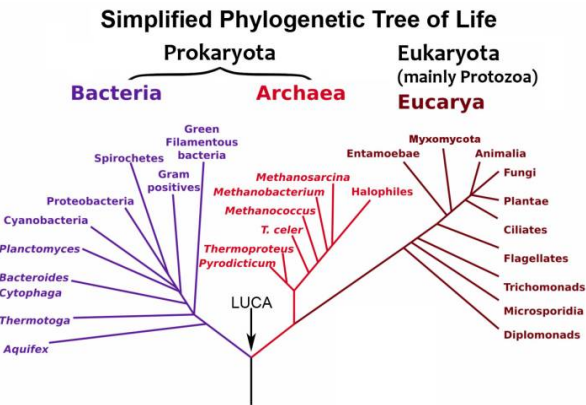
Total terrestrial carbon is thus estimated as at least 2,000 Gt in land organisms most intermixing with the 8,580 Gt in SOC in SOM or humus as active carbon stored and recycled on land, compared to just 900–1,000 Gt reactive carbon in the oceans (NASA 2011, Lal 2008: fig. 1). Observable today, as in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

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

3.10. Biodiversity of Species

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

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



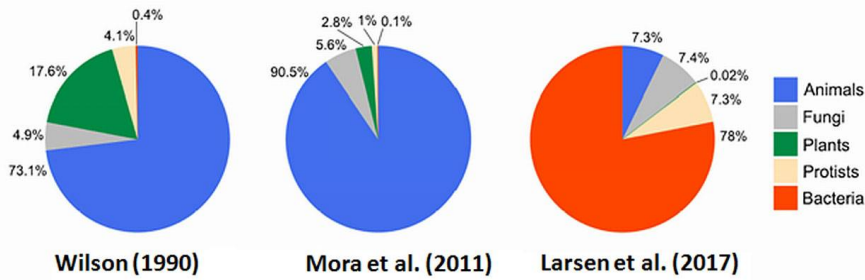
**Figure 13.** A phylogenetic tree of living things, based on RNA data and proposed by Carl Woese, showing the separation of Bacteria, Archaea, and Eukaryota (source: [https://en.wikipedia.org/wiki/File:Phylogenetic\\_tree.svg](https://en.wikipedia.org/wiki/File:Phylogenetic_tree.svg) based on Woese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

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

Species	Earth			Ocean		
	Catalogued	Predicted	±SE	Catalogued	Predicted	±SE
<b>Eukaryotes</b>						
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
Total	1,233,500	8,740,000	1,300,000	193,756	2,210,000	182,000
<b>Prokaryotes</b>						
Archaea	502	455	160	1	1	0
Bacteria	10,358	9,680	3,470	652	1,320	436
Total	10,860	10,100	3,630	653	1,320	436
<b>Grand Total</b>	<b>1,244,360</b>	<b>8,750,000</b>	<b>1,300,000</b>	<b>194,409</b>	<b>2,210,000</b>	<b>182,000</b>

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

**Figure 14.** Table of biodiversity from Mora *et al.* 2011 (ex Wikipedia from [https://en.wikipedia.org/wiki/File:Mora\\_2011\\_Predicted\\_and\\_Unpredicted\\_species.png](https://en.wikipedia.org/wiki/File:Mora_2011_Predicted_and_Unpredicted_species.png)); this shows that land has much higher biodiversity than oceans: 1.2 v 0.19 million taxa despite the oceans being better surveyed and catalogued than soils following CoML 2010 (<http://coml.org>) .

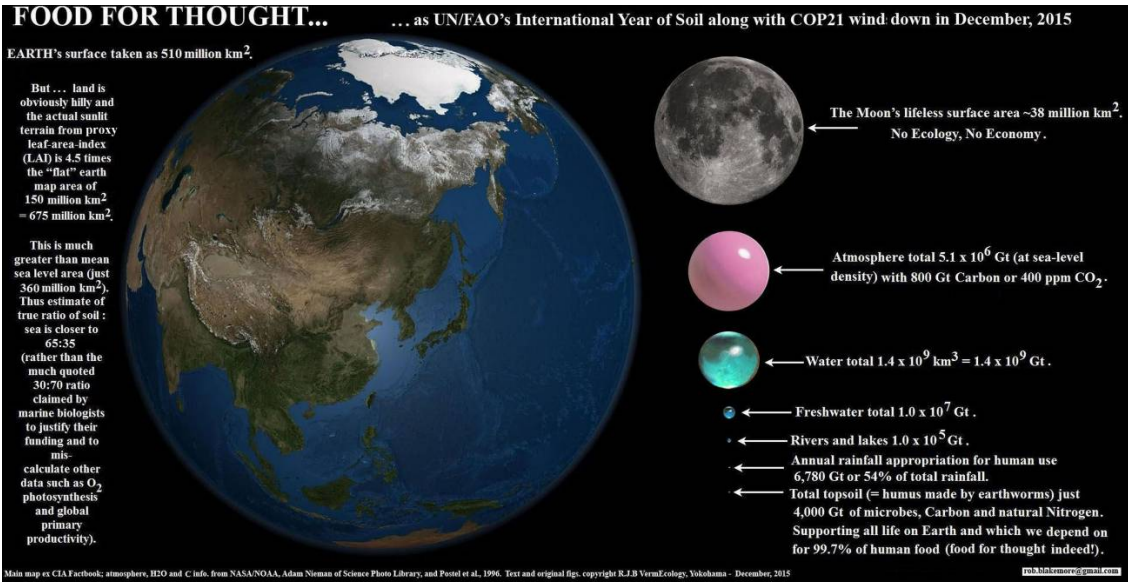


**Figure 15.** Progressive estimates of the proportions of biota showing our fundamental lack of knowledge of Life on Earth, especially of the bacteria and fungi that are dominant in many soils (modified from Larsen *et al.* 2017) .

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

3.11. Topsoil Resource

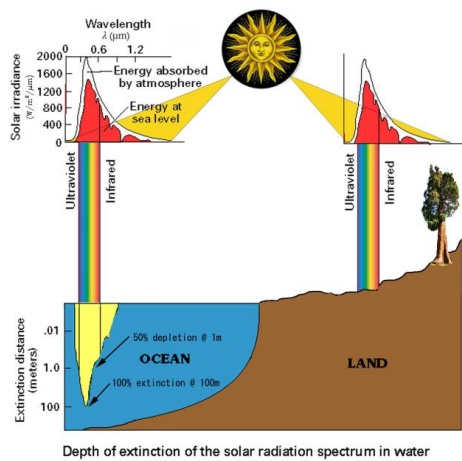
Returning to the initial questions about the Earth’s organic topsoil. It is vitally important is to determine and to conserve this vital resource or, as Darwin (1881: 39) has it in his swansong book on Earthworms: “*The vegetable mould [= topsoil humus] which covers, as with a mantle, the surface of the 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).



**Figure 16.** The moon, air, H<sub>2</sub>O and soil (from Blakemore 2015); topsoil previously estimated as ~4,000 Gt of SOM humus is herein raised about four-fold to >17,800 Gt SOM, nearly equivalent to annual global rainfall; even so it still requires much more attention and conservation efforts as it is yet the most limited and most polluted of all three vital resources (topsoil, freshwater, breathable air).

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





**Figure 17.** Photosynthesis potential of flat ocean compared to undulating and verdant land (image [archive.usgs.gov/archive/sites/ks.water.usgs.gov/images/studies/surface\\_water/solar\\_irradiance/ijc.fig1.gif](https://archive.usgs.gov/archive/sites/ks.water.usgs.gov/images/studies/surface_water/solar_irradiance/ijc.fig1.gif) modified with CC permissions). Even where light is adequate, O<sub>2</sub>, nutrients and minerals are limited in the open oceans thus limiting biomass and productivity mainly to coastal fringes.

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

3.12. NPP

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

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

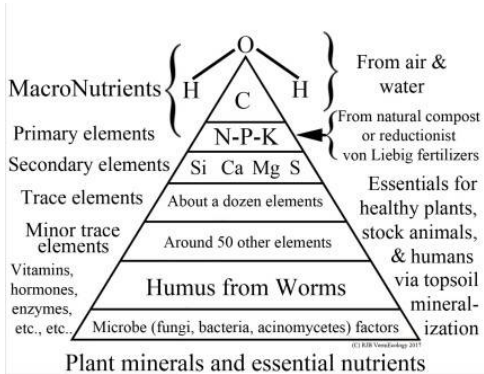
NPP Totals for 15 Gha land by authors	Rate land C g/m2/yr	Rate sea C g/m2/yr	Total land C Gt/yr	Total sea C Gt/yr	TOTAL NPP Gt C	% land	% sea
Duursma & Boisson 1994	144	72	21.6	25.9	48	45	55
Whitman et al. 1989	-	-	48	51	99	48	52
Stiling (1996)	773	152	115	55	170	68	32
UNEP (2002)	-	-	56.4	48.5	105	54	46
Campbell (2008) recalcd.	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%

\*Land and sea rates are based upon the estimated averages of Stiling (1996) and of Campbell (2008 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] .

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

Pertinent to this are calculations of land productivity per unit area from ecological quadrats that may need to be revised upwards, by ~1–5% or more, to account for terrain slope/relief (Appendix A). This too applies to earthworm surveys, conventionally tied to a flat 1 m<sup>2</sup> metric, these too may require 1–5% increase but this is minor to their doubling for more refined land surface areas.

Getting to the crux of the Net Primary Productivity (NPP) issue, a recent report stated that: “At a certainty level of 75 %, soil C mass will not change if CO<sub>2</sub>-induced increase of NPP is limited by nutrients.” (Köchy et al. 2015.). The present paper increases soil C mass by increasing soil area/volume whereas, to the conventional, but problematical, agrichemical advocates this certainty statement would imply that even more synthetic Nitrogen and other chemicals need to be added to soils. To agroecology aficionados, the same statement implies a need to recycle all organic wastes back to the soil to “close the circle”, preferably with rapid and beneficial vermicomposting, in order to fulfil what Sir Albert Howard (1945) called the Law of Return. Spontaneous generation has long been debunked and, similarly, it is not possible for any higher organism to exist without tangible resources as alluded to above: viz. gasses, sunlight, nutrients and habitat. Conventionally, soil nutrients are only considered in terms of simplistic chemicals N-P-K, whereas the proper plant requirements are complex and mainly carbon based, as shown in Permaculture’s nutrient-pyramid charted below (Figure 18).



**Figure 18.** Plant nutrient pyramid (from Blakemore 2018c - <https://vermecology.wordpress.com/>); Carbon in plants and soil is by far the most important element; atmospheric N<sub>2</sub> is used by nitrogen-fixing microbes and is also released by weathering of soils, the rates of which are substantially underestimated without terrain or relief.

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

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

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

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

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

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

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

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

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

diameter of 6,853 and a new area of 36,885,132 ha. This extra 435,132 ha (4,351 km<sup>2</sup>), which is the least possible, is only a modest 1.2% extra but increase in surface area is likely closer to 400% with finer resolution. From the worked practical examples above, its hilly terrain allows 21.25% extra land (at least) and, because soil occupies most of the land, then by 94% tortuosity and then again by 108.2% relief. This gives a practical area of  $(0.0365 \times 1.2125 = 0.044 \times 1.94 = 0.085 \times 2.082 =) \sim 0.17$  Gha which is larger than Mongolia's flat surface area: in the realm of 0.15 Gha before its own required readjustments (Figure 19).



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

### 3.15. Flaws in un-flattening the Earth?

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

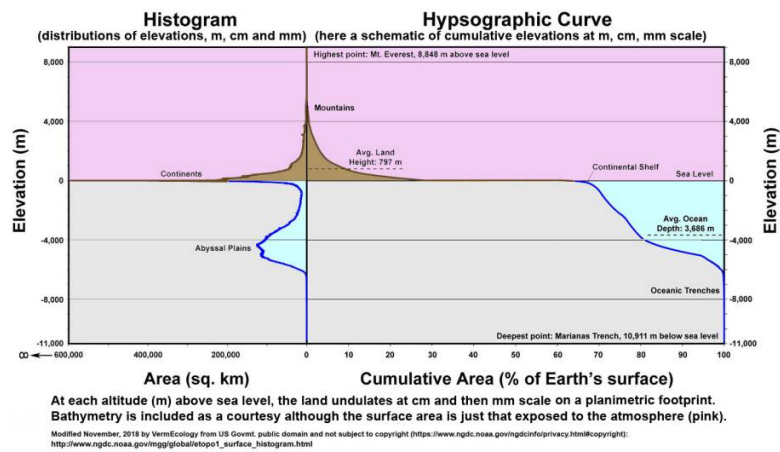
Regarding soil biomass, as carbon values are drawn from loss-on-ignition (LOI), or Walkley-Black they may include much of the microbiota (although certainly not the larger megadrile earthworms nor sieved roots), whereas microbial measurements often take smaller samples and either extract DNA or use plate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

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

4. Conclusions

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

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



**Figure 20.** New view of Earth's meaningful surface area (modified from [www.ngdc.noaa.gov/mgg/global/etopo1\\_surface\\_histogram.html](http://www.ngdc.noaa.gov/mgg/global/etopo1_surface_histogram.html)).

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

**Supplementary Materials:** Excel data files and a supplementary BD text file are attached.

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**Conflicts of Interest:** The author declares no conflict of interest.

Appendix A

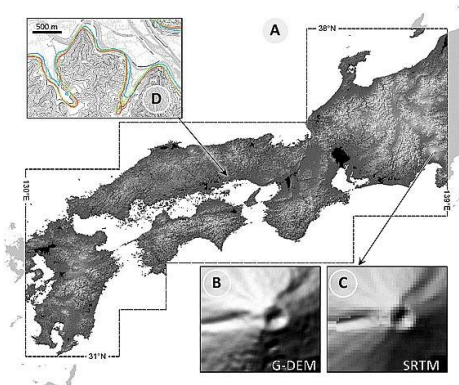


**Sampling Quadrat Slope Errors.** Regarding ecological quadrat surveys, data from these are almost always considered or presented from a planimetric viewpoint: on a flat area basis, yet truly flat land is rare. Standard quadrats have a manageable proportion of a 100 cm square with area of 10,000 cm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

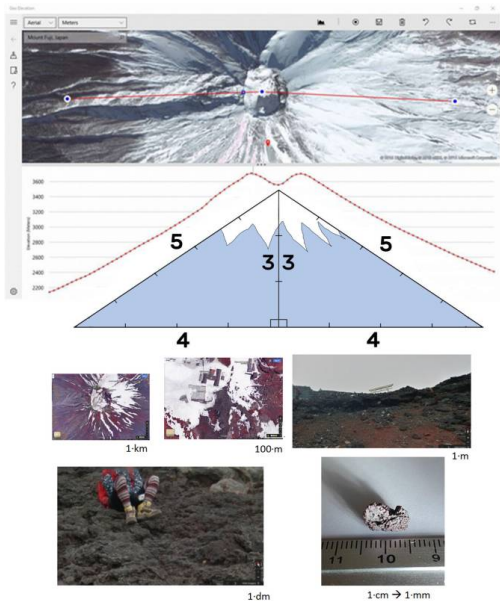
A survey's result with biodiversity or productivity from these quadrats are projected onto a lesser flat surface area and are thus variably reduced, being correct only when true topography is factored in. The obvious solution would be to ensure the quadrat is a perpendicular projection for any measurements.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

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

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



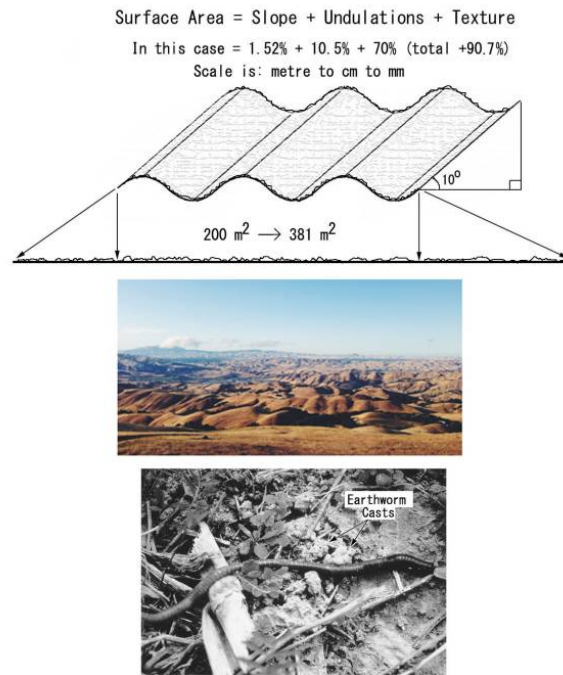
**Figure A1.** Satellite imagery of western Japan with Mt Fuji example (from Hayakawa *et al.*, 2008: fig. 1B–C with permissible repost - <https://publications.agu.org/author-resource-center/usage-permissions/>), but yet no total TMA surface area estimations are provided.



**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](http://www.microsoft.com/en-us/store/p/geo-elevation-map-elevation-chart-creator/9nblggh5wn5j), GoogleEarth, and photography by the author).

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

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

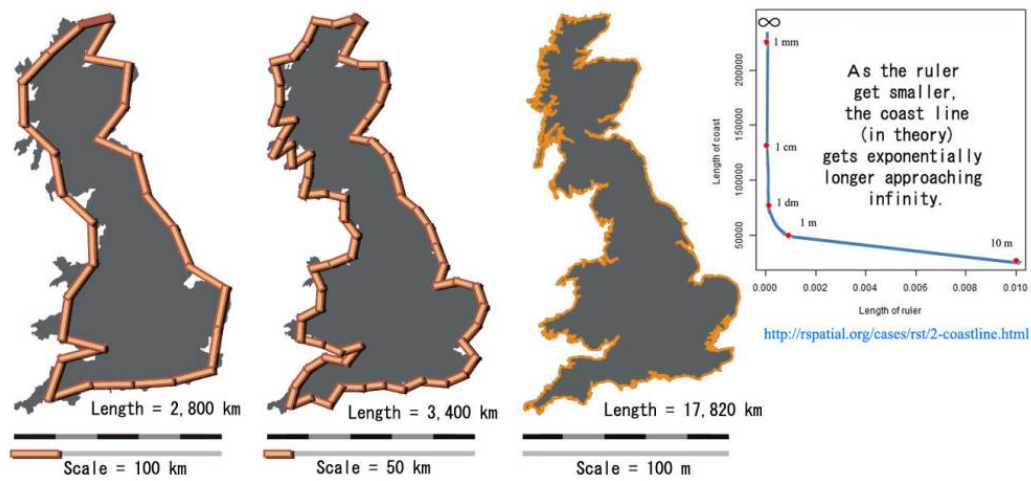


Landscape is more convoluted and the soil surface more complex

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

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

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



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

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

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

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