Veni, Vidi, Vermi...
I. On the contribution of Darwin's 'humble earthworm' to soil health, pollution-free primary production, organic 'waste' management & atmospheric carbon capture for a safe and sustainable global climate

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Abstract
Organic farming supplies more food with less ecological cost than chemical agriculture. Earthworm aspects are threefold: 'waste' recycling through compost worms and soil enhancement from endemic field worms that also form base of food-webs. Bio-physico-chemical benefits from sustained earthworm activity accrue for biodiversity, soil organic matter (SOM = worm-worked humus) derived from carbon sequestration of atmospheric CO_2 via photosynthesis/humification and nitrogen N_2 fixation from microbes rather than synthetic Haber-Bosch urea, plus greatly improved infiltration and soil-water-storage.

Just as earthworm burrows filter all rainwater, all atmospheric carbon from leaf litter/roots is processed through their intestines in 12 yr cycles as they build topsoil. Earth's total soil data are not readily available, but flat-surface estimates with ranges of 2,400-6,020 Gt of topsoil humus are newly recalculated herein as 10,800-27,090 Gt containing 6,264-15,712 Gt SOC with a median value >10,000 Gt global soil carbon. Carbon restoration in this humus resource alone has potential for rapid reduction of Mauna Loa's 400 ppm atmospheric CO_2 by ~100 ppm, i.e., to pre-industrial levels.

This review highlights that organic husbandry – with earthworms at its core – offsets CO_2 emissions (remediation) while moisture, pH, and soil temperatures simultaneously improve, increasing crop resilience and biodiversity (mitigation & adaptation). Earthworms naturally monitor & maintain healthy soils thereby solving human-generated climate & critical species extinction problems at both local & global scale. Such important considerations support 2015 Paris COP21 'Climate Change Policy' & international "*4/1000 Initiative: Soils for Food Security & Climate*" agenda.

Keywords: carbon, CO_2 off-set, food security, health, humus, topsoil erosion, species extinctions, organic agroecology, permaculture.

INTRODUCTION

Soils are back on the agenda due to urgent concerns about three inter-related issues of: carbon sequestration, water & food security. The year 2015 was designated UN's International Year of Soils, it also marked centenary of first use on the battlefields during the First World War (WW1 1914-1918) of poison gasses. These were deliberately devised by Fritz Haber (1868-1934) who had also developed an industrial system of extracting nitrogen for synthetic fertilizers and explosive munitions that earned him a Nobel prize. But as McKie (2013) summarizes: "*It's 100 years since Fritz Haber found a way to synthesise ammonia – helping to feed billions but also to kill millions, and contributing to the pollution of the planet*". After WW2 (1939-1945), disposal of stockpiled chemicals was circumvented by simplistic N fertilizers and use of toxic poisons to kill smaller invertebrates and plants just as effectively as soldiers. Thus agrichemical use intensified on both arable soil and grassland during the 1950-1970 "Green Revolution", itself highly reliant on fossil fuels and on water. Despite unintentional, deleterious consequences (e.g. Carson, 1963; Pimentel, 2005), in only 60 yrs industrialized, agrichemical farming expanded around the world and Haber-Bosch nitrogen is linked to a higher human population. The prevailing chemical-based agribusiness N-P-K paradigm denies natural ecological processes so that scientific merits of "natural" or organic farming (= modern agroecology) remain relatively underfunded, largely uninvestigated, and mostly overlooked or ignored (Fig. 1). Seemingly it is also an undeclared war on soil organisms as cultivation, noxious biocides and synthetic fertilizers are particularly deleterious to earthworms (Lee, 1985).

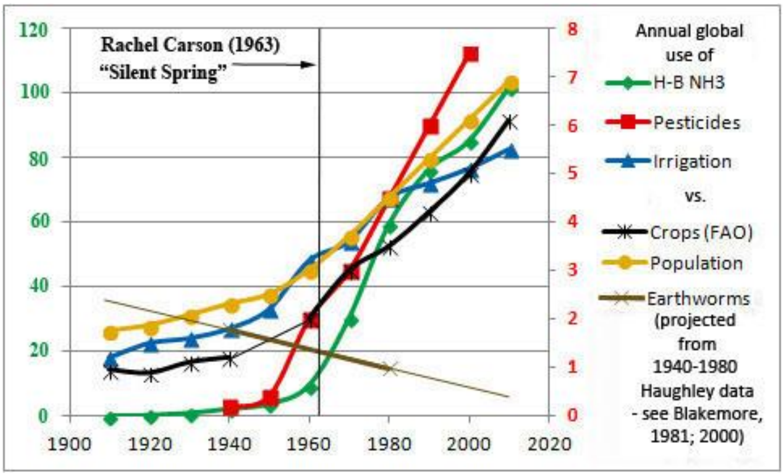


Figure 1. Indexed earthworm (m^{-2}) % decline vs. global Green Revolution using synthetic Haber-Bosch NH_3 fertilizers (Mt N/yr) (Smil, 2011), toxic biocides (Mt/yr) (Tilman *et al*., 2001-*Science* 292: 281, cedarcreek.umn.edu/biblio/fulltext/t1791.pdf) & water (FAO, Tt H_2O/yr); a more sustainable 'Brown Revolution' is now needed.

FAO (1991, 2015) report 33 % of all land moderately to seriously degraded, more so in agricultural soil that is vitally important in providing 99.7% of human food while just 0.3% comes from oceans & aquaculture (Pimentel & Burgess, 2013), even as waterways and seas are polluted by erosion runoff. Soil is also the largest fast-cycle labile carbon sink with its >2,300 Gt C equal to that of forests & mangroves (550 Gt), air (800 Gt) plus oceans (1,000 Gt) combined (NASA, 2015). Topsoil is most reactive to human disturbance and agriculture especially interrelates to climate change that also affects species extinctions. Henriksen *et al.* (2011) quote from Campbell (2008): "*The time is ripe for refocusing on soil stewardship as a key to improving water productivity, energy productivity and food security while reducing net greenhouse gas emissions from agriculture*." Realization of this simple fact is growing due to a rapid and dramatic imbalance in the atmospheric CO_2 cycle threatening global security (Lal, 2010). However, mass extinction may be seen as the most important and urgent environmental issue in a report by Rockström *et al.* (2009) (Fig. 2), followed by N_2, then climate.

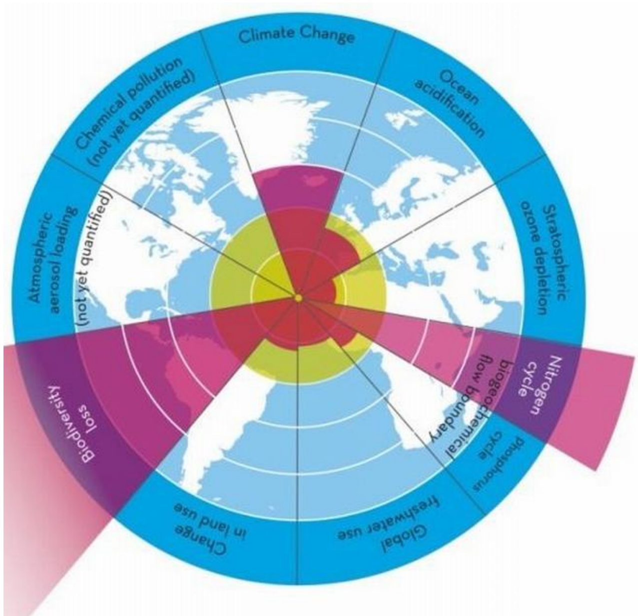


Figure 2. The nine planetary boundaries are critically exceeded for Biodiversity Loss and N-Cycle with Climate Change a lesser issue (after Rockström *et al.* 2009).

Plant photosynthesis is the only way proven to remove atmospheric CO_2 and, via plant residues, to store carbon and N in soil. If all crop residues and manure from agriculture were recycled, rather than being dumped or incinerated, the proportion of carbon held in soil may increase thus remedying twin problems of waste management and carbon capture & storage (CCS). Much promoted methods of carbon remediation such as reduced/minimum tillage and charcoal (heavily marketed as "agrichar" or "biochar") involve chemical herbicides and other applications that are toxic and/or noxious to soil fauna; reliant yet on artificial fertilizers and thus high energy use, neither offers any advantage over organic mulches and traditional composting. They are also relatively unproven unlike vermicomposting which, as a wholly natural process, is environmentally harmonious thus having true potential to resolve the ecological complexities of soil stewardship whilst doing no harm. Few studies consider non-chemical zero-till options whereas some critics (e.g. at Australia's CSIRO) naïvely or deliberately invoke chemical zero-till as being substantially equivalent to organic farming which it clearly is not (Howard, 1945; Balfour, 1977; Blakemore, 1981; 2000a).

Most soil carbon budgets are, at best, rough estimates. Basic reports were compiled before availability of Landsat data theoretically permits more exact measure of 3-D topological land surface area and of global soil stocks, although these data are not yet publically provided for some inexplicable reason. Thus all current soil carbon totals are likely underestimations requiring recalculation. Conversely, a paper from the Philippines by Racelis *et al.* (2008: tab. 6) appears to overestimate SOC by x10 in topsoil and x5 in subsoil due to simple miscalculation.

The present review is a synthesis of current knowledge; refocusing on the importance of earthworms to soil maintenance and the benefits of the resulting healthy soil to species diversity, primary production, food security, and environmental/political stability. It takes up the challenge of Rockström *et al.*'s (2009) planetary boundaries by investigating a simple fix for all interlinked problems these authors highlighted as critical but for which they offered no solutions. Aims are to define the scale of the carbon/nitrogen problem, review the practical options for remediation, and to consider viability of organic farming as a remedy to global warming and critical extinction rates. The vital role of earthworms in various natural processes, often overlooked or taken for granted – despite early advocacy from Darwin (1881) – are finally reconsidered.

The purpose of this review is to research whether conserving earthworms can serve as a simultaneous remedy for most environmental problems that relate to soil (in Figs. 1-2). At issue is the potential of organic farming – that essentially aims to "*feed earthworms*" in order to rebuild healthy topsoil (Balfour, 1949) – to achieve sustainability without loss of productivity nor at higher cost. The key question is: Can organic farming safely "*feed the world*" and do earthworms reliably monitor and mediate the process?

METHODS

Published meta-analyses and findings are integrated with re-evaluation of the author's earlier study of organic wheat and pasture in the UK, itself a tribute to the 1981 centenary of Darwin's 1881 book (Blakemore, 1981; 2000a) along with more recent studies from organic rice and sugarcane in tropical Philippines (Blakemore, 2016a, b). Since neither the topographical surface area of land nor consolidated topsoil carbon storage totals are readily obtainable, these are newly recalculated from what data is available. The potential of organic crops and pasture to trap and store substantial humus carbon on a global scale is briefly summarized and discussed. Natural inter-relationship between earthworm activity under organic husbandry and the potential for resolution of the anthropogenic atmospheric CO_2 problem is further evaluated. Green-house gas (GHG) fluxes, which by definition change constantly, are largely irrelevant to overall sequestration so are disregarded in favour of pragmatic nett soil C responses attributable to earthworms (cf. Lubbers *et al.*, 2013; Zhang *et al.*, 2013).

Conventions

Topsoil carbon is present in both inorganic carbonate (~950 Gt) and organic (~1,550 Gt) forms (Lal, 2008). By convention, soil organic carbon SOC (**tha^{-1}**) is calculated from:

$$SOC = \textit{soil carbon } \mathbf{(\%)} \times \textit{bulk density } (\mathbf{g\ cm^{-3}} \textit{ or } Mg\ m^{-3}) \times \textit{sample depth } \mathbf{(cm)}$$

A van Bemmelen (1891) value of 0.58 is generally used to convert SOM to SOC; i.e., Soil Organic Matter SOM ≈ 1.724 x SOC and thus SOC ≈ SOM x 0.58. Effectively, a proportion of say 1.5% SOC = 1.5 g carbon per 100 g soil or 15 g carbon per kg soil.

Atmospheric CO_2 equivalent sequestered in soil is given as $CO_2e \approx 3.66 \times SOC$ ($t\ ha^{-1}$) due to the molecular mass of two O atoms per C atom. Atmospheric CO_2 is increasing at a rate of ~2 ppm yr^{-1} (CDIAC, 2015a) and, since one ppm by volume of CO_2 = 2.13 Gt C (x 3.66 = 7.82 Gt CO_2), this is 4.26 Gt C yr^{-1} or 15.64 Gt CO_2 yr^{-1}.

Given 400 ppm CO_2 (Fig. 3) measures 800 Gt atmospheric C (Fig. 4) then each 1 ppm reduction of CO_2 requires ~2 Gt C be sequestered in humic soil. Carbon stocks in the field are usually expressed as total mass of organic carbon (often to 30 cm depth) per unit area. But for total inventory is it customary to report carbon concentrations to a depth of 1 m (or in top 3 m soil) in C t ha^{-1}. Whereas atmospheric and oceanic estimates are relatively straightforward due to mixing, terrestrial carbon accumulation rates are inherently variable and more uncertain. Recalcitrant carbon in layers much greater than 30 cm depth is probably most important for long-term SOC sequestration yet is the least well know of carbon pools, as discussed further in Results.

Note, 1 Mg = 1000 kg = 1 t or tonne (British, Canadian, Australian and SI in Europe) or "*metric ton*" (in US) and 1 g cm^{-3} = 1 t m^{-3}. Standard SI units are Mg (megagramme), m (metre) and s (second), but herein t or metric tonne with Gt for gigatonne (10^9 t), hectare (ha) and year (yr) are used for convenience and reasonable review comparisons.

RESULTS & DISCUSSION

The carbon climate conundrum and soil "missing sink" solution

Total cumulative CO_2 emissions from human activity from 1870 to 2013 are estimated at 390 ±20 Gt C from fossil fuels plus cement (73%) and 145 ±50 from land use change (27%); the total of an extra 535 ±55 Gt C partitioned among the atmosphere (+225 ±5 Gt C), oceans (+150 ±20 Gt C) and the land (+155 ±60 Gt C) (GCP, 2015). For 2013, GCP calculated total emissions of ca. 10 Gt C (or 39.3 Gt CO_2 with 36 Gt CO_2 from fossil fuels/cement and just 3.3 Gt CO_2 from land use change); this total is >61% higher than 1990 – the Kyoto Protocol reference year. Global emissions for 2014 were projected to increase by 2.5% to 40 Gt CO_2, this coupled with 400 ppm atmospheric CO_2 and the warmest global mean temperatures on record (CDIAC, 2015b). Slightly different calculations by Srivastava & McIlvried (2010: fig. 1) showed activity since the Industrial Revolution (from ca. 1750) added 101 Gt C to soil and vegetation but soil erosion caused 140 Gt C depletion to give net loss of 39 Gt terrestrial topsoil carbon.
Sources, stores and rates of CO_2 accumulation are summarized in Figures 3-4.

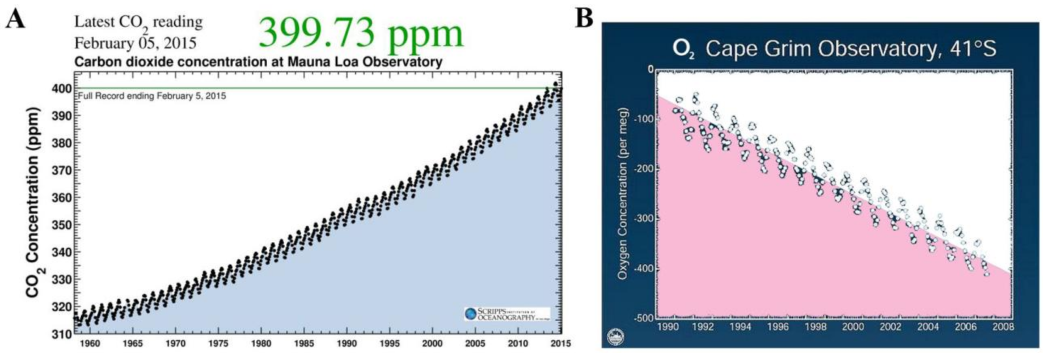


Fig. 3A. Keeling curve for Mauna Loa CO_2 (ex Scripps/NOAA); 3B corresponding decline of O_2 meg at Cape Grim, Tasmania (ex CSIRO, 2015). Isotopic studies indicate increased C ppm is from burning ancient fossil fuels rather than loss of topsoil or from volcanoes (e.g. Böhm *et al.*, 2002; Black *et al.* 2011; ABC, 2012).

Figure 3 above shows classical Hawaiian Keeling curve due mainly to fuel burning, as proven by associated decline of atmospheric O_2 in Tasmania. Figure 4 below from NASA (2011) provides key data for carbon recycling with soil (>2,300 Gt C) having ~3 Gt yr^{-1} net terrestrial uptake although much is also lost by critical topsoil erosion.

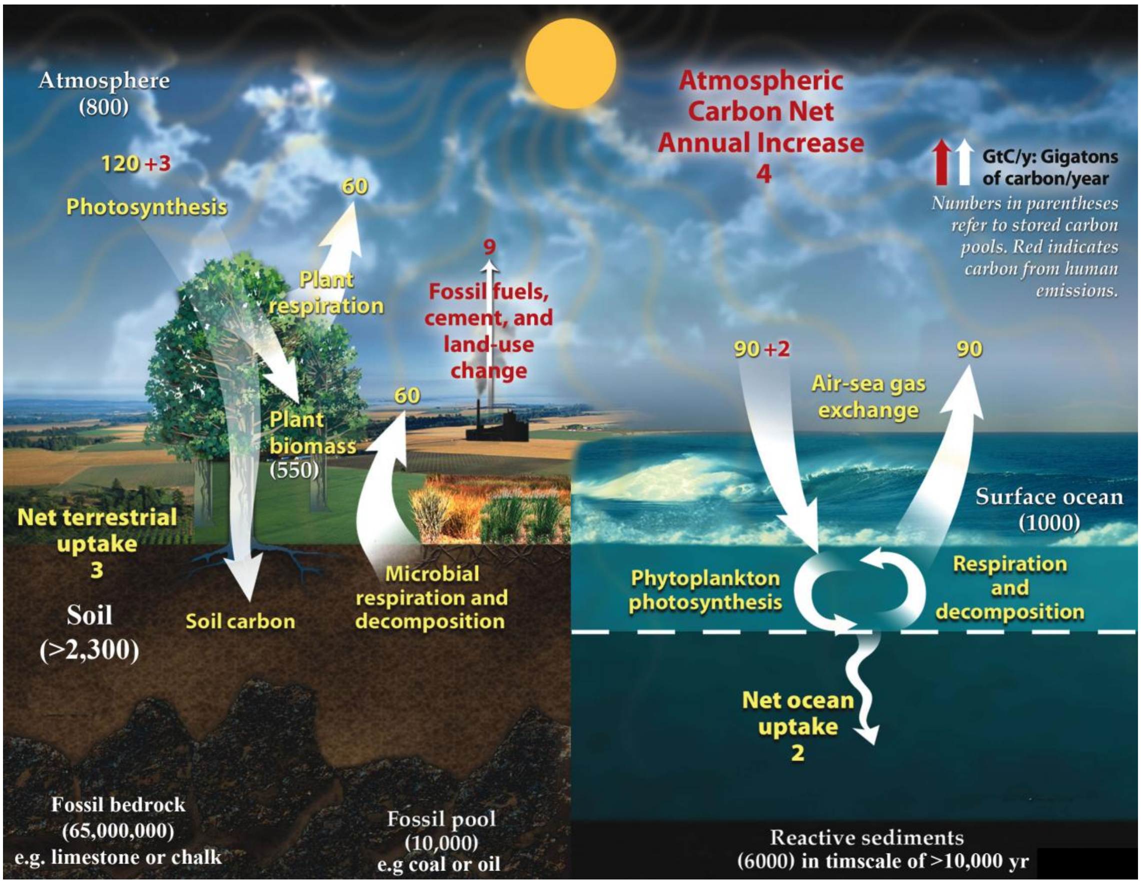


Figure 4 Annual fast carbon cycle: yellow numbers are natural fluxes; red human-induced; white is total stored C (Gt). Note land C storage & exchange (120+3) is much more important than ocean (90+2) with ratio 60:40. Soil carbon estimate in current paper is >10,000 Gt. An extra 65,000,000 Gt C is locked in fossil bedrocks as sedimentary limestone or chalk (Srivastava & McIlvried, 2010: tab. 1). While ocean organic C total is just 975-1,000 Gt, its reactive sediments cycle is >10,000 yrs. Another corrections is that "Fossil pool" should read "Fossil fuel reserves" from Houghton (2003: fig. 1, tab. 1). Image credit: from U.S. DoE (2008) & NASA (2011 http://earthobservatory.nasa.gov/Features/CarbonCycle/). Other sources are: http://genomicscience.energy.gov; https://public.ornl.gov/site/gallery/originals/Pg002_CCycle08.jpg with summary here - http://www.exo.net/~jyu/summer2012PM/carbon_cycle.pdf (Jan. 2017).

Compared to Fig. 4, average soil C from Batjes (1996) totals up to 2,500 Gt with 2,200 Gt in the first metre of topsoil. Jobbagy & Jackson (2000) give a low average of 1,502 Gt in 1 m of topsoil, plus 491 and 351 in second and third metre depths, respectively (total 2,344 Gt). More recent figures by Carvalhais *et al.* (2014) put soil storage in top 1 m layer at 2,397 Gt C (32% in tropical biomes) with just 442 Gt in above and below ground vegetation biomass (97% in forests), and they give average turnover of a carbon atom at 22.5 years cf. 10-15 yrs according to IPCC (2007). These then would also be average duration for processing of humic carbon by 'saprotrophic'/detritivore earthworms, as Darwin (1881) extrapolated from his minute observations that: "*All the fertile areas of this planet have at least once passed through the bodies of earthworms*."

However, given 800 Gt atmospheric C and an annual soil flux of 60 Gt C (as in Fig. 4) turnover time for all soil carbon may average (800/60 =) 13.3 years. This rate is further supported from IPCC (2007) data stating: "*On average a carbon atom spends about 5 years in the atmosphere, 10 years in terrestrial vegetation*". Thus a possible maximum rate of all atmospheric CO_2 reprocessed through the intestines of megadrile earthworms whilst they produce humus in soil is deduced as between 10.0-13.3 yrs with median value 11.65 yrs or ~12 yrs as alluded to in the Abstract above.

Surprisingly, since it is basic information about the planet's support system, accurate figures are not readily available for total (dry) humus in Earth's topsoil. Low estimates from Burningh (1984) and, partly, from Kovda (1974) of about 2,400 Gt comprising ca. 1,400 Gt of carbon that is about the same as 1,500 Gt C proffered by http://4p1000.org (from IPCC, 2012; cf. Fig. 4 above from NASA which has 2,300 Gt C). Whereas a highest estimate by Bohn (1976) is 3,000 ± 500Gt of SOC (and since SOM = 1.72 x SOC this gives maximum of 6,020 Gt global humus). Thus a range estimate is 2,400-6,020 Gt, or median 4,210 Gt dry humus globally, or about equal to annual human water volume use (~4,000 km^3 yr^{-1} = 4,000 Gt yr^{-1} H_2O from FAO, 2014a). Nevertheless, it may reasonably be argued that topsoil is a more limited and therefore more valuable global commodity because its replacement time is much longer: often quoted at a scale of decades or centuries rather than annually for rainwater. [E.g., FAO (2015: 103) estimate just 0.15 t ha^{-1} yr^{-1} topsoil formation; if on 9.5 Gha of non-ice/desert land = 1.4 Gt yr^{-1} globally. Cf. Darwin (1881: 173) who estimated about 15 tons of surface castings per acre on pasture/commons land (= 33.6 t ha^{-1} yr^{-1} x 1.6 Gha arable land = 54 Gt yr^{-1} globally), this about equal to nett topsoil loss of 33 Gt yr^{-1} from FAO (2015)]. Fig. 5 graphically summarizes data (from Blakemore, 2015).

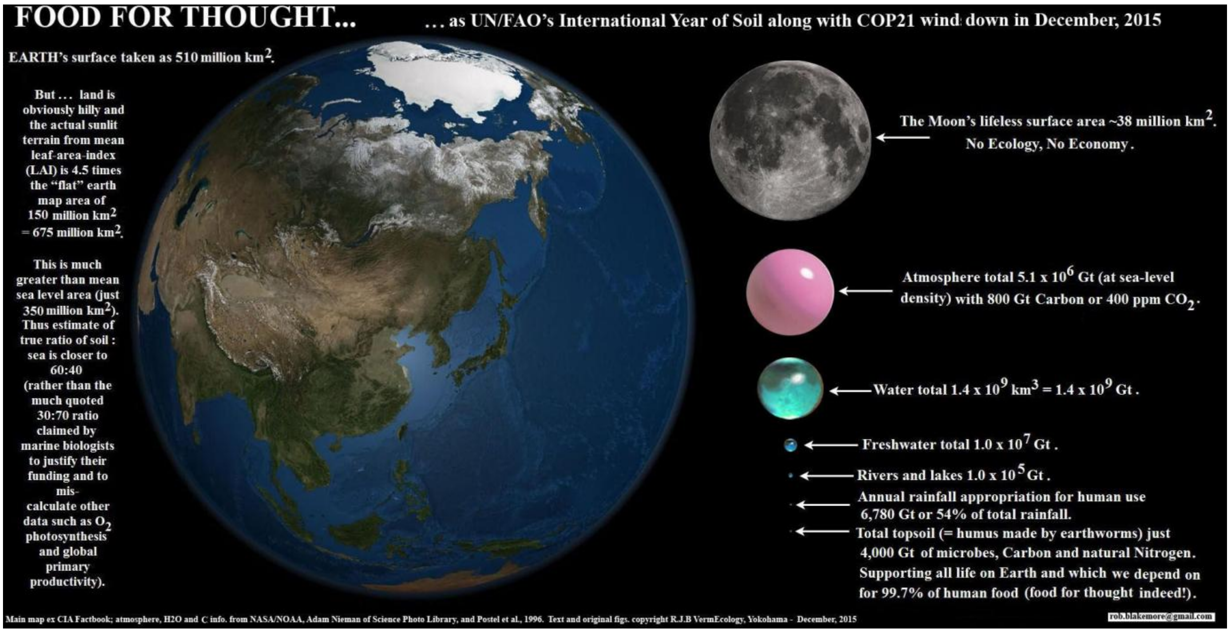


Figure 5. Comparison of global surface area and relative volumes of air, water and humic topsoil, the latter apparently less than total rainfall appropriation. The relatively minute topsoil resource vital for our survival is both most precious and least well-studied – funds going mainly to space or aquatic research. It is likely however that the total topsoil calculations are widely underestimated due to omission of topography and of other important factors, as are explained in the text.

Pasture/rangeland requires special consideration as a major global C sink, being the largest actually or potentially managed land use area as shown by new data in Table 1.

Table 1. World area under agriculture and pasture recalculated from FAOSTAT, 2013, 2015; World Bank, 2015 and IAEES, 2015 (proportional figures in braces).

Category	World land area billion ha (Gha)	% land area (approx.)
Agriculture (total)	5.4 (i.e., managed lands)	36-38
as pasture/fodder crops	(3.6)	(24)
as arable (cultivated)	(1.6)	(11)
as permanent plantation	(0.2)	(1)
Other land not farmed	5.0 (e.g. desert, ice, grassland)	33
Forest and woodland area	4.1 (~60% virgin : 40% secondary)	28
Urban	0.4	3
Total land area	14.9 (at least, due to terrain!)*	100

*Cf. Jobbagy & Jackson (2000: tab. 3) have SOC 12.1 Gha in soil + 2.8 Gha in extreme desert, rock, ice/water from Jackson *et al*. (1997: tab. 2) totalling 14.9 Gha **flat** land too!

Regarding Table 1, whilst no precise figures are known (ISRIC – not even its SOTER SOil & TERrain Programme, IUCN, NASA, NOAA, USDA-NRCS and USGS pers. comms. to RJB in 2014-16), total land area is a paradoxical 'true fractal' and may be doubled to account for topographical landform terrains (e.g. corrugated hills & valleys) from 14.9 Gha to at least 30 Gha. It is likely doubled again for soil undulations and microrelief (to scale of cm^3 say for worm castings as in Fig. 6) to ~64 Gha. This datum compares to ~36 Gha of flat ocean that is often mistakenly given as ~70% of total surface area of 51.0 Gha, as if the land were as flat as the ocean! Recalculation of Earth's total undulating topography – its actual surface area as is exposed to sunlight for photosynthesis – are thus 64 + 36 = ~100 Gha for a **true ratio 64 : 36 of soil : sea**.

As a simple example: Mt Fuji that is visible from Tokyo/Yokohama is 3,776 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. 1,130 km^2. However, the actual surface area of this near-perfect, cone-shaped volcano is 2,290 km^2, i.e., approximately double the flat surface area. Secondary undulations and micro-terrain could reasonably be assumed to double this again to ~4,580 km^2. Japan itself is particularly mountainous yet is claimed just 377,900 km^2. If also quadrupled (x 4) to account for hilly 3-D terrain, the actual undulating land surface is ~1.5 million km^2 (= Mongolia's flat area) but such a reasonable figure cannot be found elsewhere so Japan is classed as a "small" country.

Whilst the bathymetry of the sea-floor is exquisitely mapped, extensive enquiries by the author with NASA-USGS Landsat program authorities surprisingly failed to yield this basic information on global land topological surface area AMSL (above mean sea level). In lieu of this, another possibly meaningful value for true land surface area is from the global mean leaf-area-index (LAI) proxy, i.e., an approximation of undulating land exposed to photosynthesis sunlight (including deserts, grassland and tundra but excluding bodies of water), which is set at 4.5 as calculated by Asner *et al.* (2003). From the conventional estimation of total global **flat** horizontal land surface of 149 million km^2 (= 14.9 Gha) x 4.5 LAI, the land topography amounts to ca. 670 million km^2 or 67 Gha which is greater than the globally accepted surface area of flat seas (ca. 360 million km^2 or just 36 Gha) thereby vindicating my estimate above of ca. 64:36 land:water rather than the ca. 30:70 ratio often falsely claimed by marine biologists to justify their excessive share of limited research funding (as already noted for Fig. 5).

Recalculation of total topsoil carbon storage

From LAI correction, the totals of 2,400-6,020 Gt dry humus presented above (and Fig. 5) may be newly recalculated x 4.5 LAI to give revised total range 10,800-27,090 Gt humus containing (SOC ≈ SOM x 0.58) between 6,264-15,712 Gt carbon with a median value >10,000 Gt global SOC. This terrain allowance may account for 'residual land sink' (formerly the 'missing sink') in global C budget. But even this is likely an underestimation allowing for carbon in glomalin, deep soil data and living or dead roots.

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 Walkely-Black method itself underestimates total C with a correction factor of ca. 1.3 often required, whereas latest techniques using mid-infrared (MIR) spectroscopy may give more accurate readings. These three factors combined would surely increase soil SOC totals.

Relating to above ground LAI are underground root-area-indices (RAIs) with fine roots a prominent sink for carbon, often much greater than that of vegetation above ground: E.g. Jackson *et al.* (1997) estimated average fine root biomass between 0.3-1.5 kg m^{-2} and total root biomass of 292 Gt containing 19.9 Gt carbon and representing 33% of total annual net primary productivity. Roots are routinely excluded from soil carbon analyses by manual removal and sieving of samples. Some vegetation surveys, but not all, make allowance for below ground biomass and for both living and dead materials.

Total organic carbon and SOM lost from topsoil

Despite shortcomings, empirical data is that SOM carbon has been substantially depleted in the last 60 yrs due to poor management leading to substantial soil erosion around the world (e.g., GLASNOD, 1991; MEA, 2005; Pimentel, 2006; FAO, 2015). The fate and equivalent cost of this lost SOM may not be fully known but an aim for conservation must be commendable as need for topsoil restoration is an urgent priority.

Buringh (1984: tab. 3.) gave average soil carbon (to depth of soil) in all croplands and grasslands as 109 t ha^{-1} and in forest soils as 208 t ha^{-1} and estimated loss due to conversion from forest to grassland at 28% and from forest to cropland at 48%. Agricultural soils were found to contain about 20-80 t ha^{-1} C in the top 20 cm and Buringh (1984) noted that annual loss of organic matter from soils (he estimated at

2.5-7.5 Gt) was a serious problem that probably contributed to CO_2 in the atmosphere. However isotope studies refute this as a major factor (as noted above for data in Fig. 3).

According to Prof. Rattan Lal, director of Ohio State University's Carbon Center (C-MASC, 2015), the world's cultivated soils have lost between 50-70% of their original carbon stock, much of which has oxidized upon exposure to air to become CO_2. Lal & Follett (2009) estimated losses of 45-85% of SOC when natural vegetation is converted to intensive arable. Australian figures suggest the legacy of clearing native lands for agriculture depleted SOC by 40-60% releasing at least 150 Gt of carbon dioxide. A long-term Australian trial started in 1979 showed that continuous wheat cropping reduced SOC by "400 kg/ha/year" (= -0.4 $tha^{-1}yr^{-1}$) but a carbon conserving system increased it by "185 kg C/ha/year" (= +0.185 $tha^{-1}yr^{-1}$) (Chan, 2008).

Depletion of limited topsoil is a major problem, as Crawford (2012) summarizes: "*we have about 60 years of topsoil left. Some 40% of soil used for agriculture around the world is classed as either degraded or seriously degraded*". Blakemore (2010) also noted this, with a cost of this loss in the US alone estimated at $125 billion per year; and more recent data indicates that land degradation costs as much as $10.6 trillion each year, equivalent to 17% of global GDP (ELD, 2015). On the positive side, contributions of invertebrates such as earthworms to waste recycling and soil formation has a World economic benefit put at $785 billion per year (FAO, 2014c). The value of food production in 2010 was 2.9% of global GDP estimated by the World Bank (2015) at about $75 trillion, making agriculture worth about $2.2 trillion yr^{-1} although the figures from CIA Fact Book (2015) are 6% of GDP for Agriculture amounting to $4.5 trillion yr^{-1}. Neither of these totals take into consideration that food is a basic essential for survival nor do they explain what we should eat if agriculture fails.

Conant *et al.* (2001) reviewed 115 studies of carbon in improved grassland management, including addition of manures with two studies introducing earthworms, reporting an average SOM of 331 t ha^{-1}. A 0.58 van Bemmelen correction gives a mean SOC value in temperate grassland of 192 t C ha^{-1} which is slightly below the finding in a 1,000 yr-old permanent pasture at Haughley of 222 t ha^{-1} of C reported by Blakemore (2000a).

Official 'blind spot' for organic farming and earthworms

The IPCC's Fifth Assessment Report (IPCC, 2014) makes mention neither of organic agriculture nor earthworms and barely considers soils (while citing marine and aquatic systems hundreds of times); searching "*earthworm*" on The Soil Association's (2009) "*Soil Carbon and Organic Farming*" and FAO's (2011) "*Save & Grow*" guide each had only one hit. Lal (2004) mentions them twice and Leu (2007), in listing four previous SOM studies, only mentions "*earthworms*" in passing once. The Global Carbon Project has dozens of listings for "*ocean*", five for "*soils*", but none at all for "*earthworm*" (GCP, 2015 - http://www.globalcarbonatlas.org/?q=en/search/node/soil).

What is blatantly missing from almost all pertinent reports is reference to the importance of earthworms to net carbon storage and the sustainable functioning of the soil ecosystem. Yet even in their most menial roles, earthworms are claimed either to exacerbate GHGs (e.g., in a report authored by doctoral student in Lubbers *et al.*, 2013) or to ameliorate them (e.g., Zhang *et al.*, 2013), as was already debated by Edwards (2009). However, gas fluxes are highly variable and relatively irrelevant when compared to the mass storage of carbon withdrawn from the air (see Fig. 4). What these latter flux reports also miss is that without earthworm activity it would become necessary to 'geoengineer' each m^3 soil matrix with reticulated soil pores and miniature pumps in operation day and night, also to find alternative means of mixing the soil layers and routine incorporation of all surface litter. Moreover, it is their activities that create habitats and 'highways' for many other soil organisms as well as distributing propagules of mycorrhizal fungi and other beneficial microbial symbionts. As noted by Kretzschmar (1982), earthworms construct up to 9,000 km of burrows per hectare thereby enhancing root penetration, aeration and water infiltration. This in addition to their key role as the basis of almost all terrestrial food-webs – both as common prey and as ultimate detritivore (Blakemore, 2015). In other words, we have no viable alternative to the many ecological services earthworms freely and relentlessly provide.

Figure 6 graphically demonstrates earthworm effects in humus formation, soil structure and plant yield for just one trial plant-soil-worm combination in a time period of weeks.

Figure 6. Effects of earthworms on soils & plant growth (after 2 weeks); note that agrochemical trials use sterilized "dirt" to avoid such variability 'complications' rather than embracing soil biological benefits, as advocated by Blakemore(2012b).

Role of earthworms in carbon sequestration and yields in pasture soils

Of the many studies on soil carbon sequestration, only a few consider earthworms. Yet in New Zealand, Stockdill (1982) reported up to 72% increase in pasture production in soils when earthworms were present and that water infiltration rate doubled, the moisture holding capacity increased by 17% and available moisture increased by 18 mm (24%) for the top 30 cm of the soils tested. Organic carbon sequestration increase in those pastures that supported earthworms manifest as extra 21% that averaged 2.54% vs. 4.46% soil carbon when earthworms were absent vs. present in Wehenga silt loam to 10 cm soil depth (as was summarized by Yeates, 1991; tab. 3).

Blakemore (1994, 1979) had pasture yield increases of 27-64% with added earthworms. An earlier 1981 study of a 1,000 yr-old organic pasture at Haughley had highest earthworm counts (424 m^{-2}), stored 222 t ha^{-1} SOM carbon, plus its soil moisture capacity was 90% above arable fields (Blakemore, 2000a; and Fig. 8). Should all organically managed pastures achieve such ideal levels of soil organic carbon (SOC) as at Haughley, then total C (222 t/ha x 3.6 Gha pasture globally) = ca. 800 Gt which exactly matches current atmospheric C concentration. Aiming to sequester just 1% of this (8Gt) in topsoil in four or five years would match human emissions and help reduce atmospheric CO_2 accumulation by -2 ppm from its current growth rate of +2 ppm per yr.

Indeed, Conant *et al.* (2001) reported C sequestration in improved pasture management (including manuring and two studies with earthworms) means of 0.54 t C·ha^{-1} yr^{-1} (after 23.7 yrs) giving potential of (0.54 t/ha x 3.6 Gha pasture globally) = ca. 1.9 Gt C/yr.

Pasture improvement may be more rapid, for instance Yeomans (1958) reported: "*Ten cm of new topsoil was created in three years – something that was previously thought to take around 800 years! Earthworms emerged in abundance, the size of which (over 60 cm or 24 inches) had never been seen before in the [Riverland] Region.*" (Fig. 7).

Figure 7. Keyline Outcomes: The photo shows lush growth on what had been very low-grade pastures. The other picture shows the unidentified worms he reported (after Yeomans 1958: Pl. 30). Quotes and photos courtesy of Laceweb Homepage concerning P.A. Yeomans Keyline system on Nevallan farm, Richmond, NSW: http://www.laceweb.org.au/Chapter%20Three.htm Photo 16; and www.soilandhealth.org/01aglibrary/010126yeomansII/010126toc.html [July, 2005].

In addition to their humus contribution, Hodson (2009) claimed that earthworm-produced calcite alone could lock up as much carbon as 0.564 t C ha^{-1} yr^{-1}. Given total UK managed agricultural holdings of 17.1 million ha, this ideally translates as 10 Mt yr^{-1} C (= 35 Mt CO_2e or ca. 13% of UK's net emissions in 2013 of 464.3 Mt).

If UK and other countries committed wholly to organic husbandry with results like those reported by Blakemore (2000a; 2016b) and herein it may help resolve its emissions issue and avoid expensive and misguided geo-engineering projects (such as UK's £1.6m SPICE program). Lal (2008) makes similar arguments, albeit without considering earthworms.

Organic husbandry redress to SOC loss

Lal & Bruce (1999) reviewed the potential of the World's cropland soils to sequester C and mitigate the greenhouse effect: Carbon storage potential of soil organic matter (SOM), as both volatile and resilient humus, in US alone was calculated by them to account for an average of 288 Mt yr^{-1} (= 0.11 Gt yr^{-1} CO_2e) for at least 30 yrs, or perhaps ~1.7 ppm yr^{-1} reduction x 30 yrs = ~50 ppm off Mauna Loa's 400 ppm bringing it to the desired 1990 level of 350 ppm by 2030.

To increase soil organic carbon from 3% to 5% in the upper 10 cm of soil, it is estimated that 24 t ha^{-1} C would have to be added (Baldock & Broos, 2008). Since plant residues contain approximately 45% C, this would equate roughly to 50 t ha^{-1} dry plant matter. The Soil Association's "*Soil Carbon and Organic Farming*" (Soil Association, 2009) reports 20-28% higher soil carbon from comparative studies which would result, they claim, if organic agriculture was globally adopted, in potential offset of around 11% of all green-house gas (GHG) emissions each year for 20+ yrs.

A meta-analysis of 68 datasets comparing conventional with organic farming (Leifeld & Fuhrer, 2010) revealed SOC in organic systems increased annually by 2.2% on conversion. These authors somewhat misinterpreted the philosophy, economics and ecology of organic farming as they criticized disproportionate application of organic fertilizer compared to conventional farming as being somehow unfair. Nevertheless, their table 1 provides a useful list of comparative studies, with variable reliabilities, and they do concede that soil carbon sequestration is a key measure in agriculture to counterbalance large emissions of agriculturally induced green-house gasses (GHGs).

Gattinger *et al.* (2012) reported enhanced topsoil C on organic farms in a meta-analysis of 74 pair-wise comparisons finding extra stocks of +3.5 t ha^{-1} and rate +0.45 t ha^{-1} yr^{-1}. They noted few data available for tropical regions, which the accompanying study (Blakemore, 2016b) aims to help redress, nor for deeper subsoil. The Swiss DOK study found 64% of total SOC was at 20–80 cm depth (Fliessbach *et al.*, 1999; 2007). Birkhofer *et al.* (2008) looked at many factors in this 34 yr Swiss DOK trial, as already reported by Mäder *et al.* (2002), somewhat similar to results in Blakemore (2000a).

Another meta-study by Rodale Institute in 2014 also concluded that if all cropland were converted to their regenerative model it would sequester 40% of annual CO_2 emissions; adding pastures to that model would add another 71%, effectively overcompensating for the world's yearly carbon dioxide emissions (Rodale, 2015). Moreover, their side-by-side trial after 30+ years (slightly less than the Haughley trial that was 42 years when reported by Blakemore, 1981; 2000a) showed organic : conventional yields to be equivalent over a range of crops (but organics higher in drought years), with energy input lower by "1,300 MJ/acre/yr" (= 526 $MJha^{-1}yr^{-1}$), greenhouse gases lower by "500 lbs CO_2/acre/yr" (0.56 $tha^{-1}yr^{-1}$) and profits higher by "US$368/acre/yr" ($908 $ha^{-1}yr^{-1}$) (Rodale 2015). Pimentel *et al.* (2005) reviewed the Rodale results after 20 years.

Total potential carbon sequestration under the three crops noted by Blakemore (2016b), if all farms fully converted to organic on a global scale, was found to equals 53.1 Gt CO_2e which is equivalent to ca. 7.3 ppm atmospheric CO_2 reduction.

Can organic farming reliably and safely "*feed the world*"?

Accepting that organic farming can trap carbon in soils, the next question of whether natural farming in all its manifestations can meet increasing food demand has already been answered by its bringing us from the origin of life, via Neolithic agriculture from 10,000 yrs ago as far as the 1960's and to industrial agriculture's "Green Revolution" (see Fig. 1). As already noted, soils provide 99.7% of human sustenance (FAO, 1991; 1998; 2014b; 2014c; Pimentel, 2005; Blakemore, 2012a) whereas seas & wetlands are relatively irrelevant ecologically and economically since photosynthesis only occurs superficially and just 0.3% of human food comes from oceans & aquaculture combined (Pimentel & Burgess, 2013), with about 99% of this from coastal areas gaining nutrients (and pollution) from agrichemical soil runoff and natural erosion (UNESCO, 2015).

Cultivations combined with agrichemicals in the last 60 yrs have eroded topsoils and, rather than continued mass production, there is now a call for "*appropriate technology*" (Toffler, 1980). Failure of industrial farming to provide safe and adequate food is recognized in extensive reports such as by UNEP's IAASTD (2008) which says of Organic Agriculture "*The resulting increased food variety and overall per-area* *productivity has led to diversified and increased nutrient intake and improved food safety and food security*". But even this sustainability website gave no result for a search of "*earthworm*" although their "*Towards Multifunctional Agriculture*" paper did acknowledge "*Permaculture*". A recent study by De Schutter (2010) reported that small-scale sustainable farming can double food production within 3-10 yrs, lower costs, reduce unemployment (see also Green & Maynard, 2006; Maynard & Green, 2006) whilst also combating climate change. A brief summary review provided by FAO (2015) also concluded that increased yields on organic farms are more likely if the departure point is a traditional system. Halweil (2006) gave examples of studies in India and Africa where converting to organic farming increased average yields by 20-93%; this study also gives a particularly balanced report on other important factors.

In Africa, it seems food security issues may hinge on organic agriculture as studies by UNEP (2008) showed yields raised by an average of 116% (128% higher for East Africa), whereas introduction of conventional (i.e., non-organic) agriculture to Africa actually lowered food production by 10% per person when compared to the 1960's

Another broad meta-analysis by Badgley *et al.* (2007) concluded organic agriculture can supply all global food need supporting an earlier report by Balfour (1977) that organic production at Haughley was 15% higher than conventional over a 20 year period. This finding was endorsed after 40 years by Blakemore (2000a; 2016b) and sections of the farm studied had significantly increased wheat (by average 16.2%), higher SOM, and enhanced soil moisture in organic fields associated in each case with higher earthworm activity and diversity when compared to adjacent conventional fields. Moreover, Rodale Institute's recent 30 yr report (Rodale, 2015) showed in side-by-side comparison that organic matched conventional yields (for lower costs) and that "*In 4 out of 5 years of moderate drought, the organic systems had significantly higher corn yields (31 percent higher) than the conventional*". Data in an Appendix demonstrates cereal yield of an organic farm at Bhopal in India at >3 times higher than conventional averages.

While not considering organic farming *per se*, a recent meta-analysis shows earthworm presence corresponding to crop yield increases of 25% (van Groenigen *et al.*, 2014), which is comparable to average ~39% extra organic yield in soils with earthworm proliferations determined in accompanying studies by Blakemore (2016b).

Conversely, two reports primarily authored by PhD candidates (Seufert *et al.*, 2012 and

Ponsio *et al.*, 2014) claimed **all** organic yields lower than conventional although their finding differed somewhat. Moreover, Mäder *et al.*'s (2002) report on a 21-year study of agronomic and ecological performance under biodynamic, bio-organic, and conventional farming systems just in Switzerland (FiBL DOK-trial) did find bulk crop yields 20% lower in the organic systems, even though input of fertilizer and energy was reduced by 34-53% and pesticide input by 97%. Surprisingly their organic carbon results did not differ significantly across treatments. However, they did find enhanced soil fertility and higher biodiversity in organic plots – including more than three times the number of earthworms – which these authors concluded would render these systems less dependent on external inputs and thus more resilient to climatic shifts.

Although Birkhofer *et al.* (2008) seem not to have emphasized the carbon sequestration potentials, they reported (in FIBL, 2015) that organically grown crops require 30-50% less energy per unit area (including energy for fertilizers and pesticide production – see also Pimentel *et al.*, 1983). Compared to *in situ* N-fixing microbes and composts, synthetic urea (46% N), although highly financially subsidized, is inefficient due to volatility loss to the atmosphere and to runoff, with nitrate pollution in drinking water leached from crop soils posing a stomach cancer risk (WHO, 1985; INCHEM, 2015).

Organic farming status, disproportionate funding, health and economic issues

Despite growing at an annual rate of 8.9% per annum from 2000-2011, worldwide just 0.9% of farmland is managed organically with approximately 37 million hectares (91 million acres) FiBL-IFOAM (2014) data. However, IFOAM President Andre Leu (quoted from Lappé, 2014) points out that "*Fifty-two billion dollars is spent annually on agriculture research worldwide, but less than 0.4 percent* [i.e., ca. $200 million] *is spent on organic farming systems*". The USDA in 2001 spent $5 million on organic agriculture research compared to $210 million on biotechnology (FAO, 2013). Such disparity partly explains why basic information on the capabilities and properties of organics and worms are still relatively obscure and unappreciated, hence this review. FAO (2013) also shows global public spending on agricultural R&D was $31.7 billion in 2008 whereas most organic research is left to individuals or charitable trusts.

In comparison, NASA's annual budget is $10-20 billion each year since 1958; the Large Hadron Collider has cost about $13.25 billion with a recent paper ("Aad, G. *et al.*, 2015") having 5,154 authors; NOAA – the US National Oceanic and Atmospheric Administration with ambit covering everything *except* soil – has budget request for

2015 totaling $5.5 billion; and cost of CoML (http://www.coml.org/) was over $1 billion. Just one of the many hundred marine institutes, JAMSTEC in Yokohama, receives about twice as much as organic research at ca. $400 million p.a.. This is a sad indictment of our research priorities given soil's importance to species survival and its threatened status with some predictions that all topsoil may be lost in another 50-60 years (while the stars, Higgs' boson and deep-sea fishes will all still be there tomorrow). Wheeler (2004; 2010) advocates triage in science and asks: "*What NASA would do?*"

Since myriad aquatic, atmospheric and astronomical institutes are fully supported, it is a complete mystery why not one dedicated "*SOIL ECOLOGY INSTITUTE*" exists nor a full-time, specialist megadrile earthworm eco-taxonomist remaining at a research facility or museum anywhere on Earth (as was lamented by Blakemore, 2010; 2016a).

In contrast to the potential of agroecology, the N-P-K 'agribusiness as usual' model has largely failed. Giampietro & Pimentel (1993) and Pimentel & Giampietro (2008) estimated that 10 kcalories of fossil fuel energy are expended in non-organic food system per one kcalorie (= 4.184×10^{-7} vs. 10^{-6} MJ) of food energy derived; they also estimate fossil-based pesticides consume a significant amount of global energy. World agri-biocide use runs at about 2.5 million t yr^{-1}, often with negative effects on non-target organism (Carson, 1963; Pimentel, 2005; IAASTD, 2008 and see Fig. 1). For example, glyphosate that is routinely used as a herbicide but was originally patented as a strong metal chelating agent or pipe cleaner and antimicrobial, has been shown to reduce growth rates, activity and reproduction of earthworms as well as causing risk of local extinctions (e.g., Santadino *et al.*, 2004; Gaupp-Berghausen *et al.*, 2015; https://en.wikipedia.org/wiki/Glyphosate). This correlates to its reported long-term health risks identified in the laboratory when Seralini *et al.* (2012; 2014) replicated the manufacturer's experimental test methods using Sprague–Dawley rats (as per sponsored Hammond *et al.*, 2004 paper) but extended the trials from just 3 months to 24 months. Deleterious effects are also recorded in human exposure to such chemicals or to plants sprayed with them (Pusztai *et al.*, 2003; Krüger *et al.*, 2014; El-Shamei *et al.* 2012; Sirinathsinghji, 2015; Jayasumana *et al.*, 2005; I-SIS, 2015; WHO, 2015). The latter WHO report lists glyphosate as '*probably carcinogenic to humans*'.

Such risks are avoided with organic farming's methods of weed and pest management, as UN's FAO states (FAO, 2015): yield advantages are attributed to a combination of factors including fewer losses to pests and disease, as was noted in the current rice paddy studies (Blakemore 2016b and unpublished). How much intrinsic plant defence against pests and pathogens is due to a synergistic trophobiosis under organic farming merits investigative research (e.g., Loening, 2004; Blouin *et al.*, 2005; Paull, 2007).

Effects of organic farming on earthworm abundance

Pfiffner & Balmer (2011: fig. 1) charted 14 studies of organic farming and earthworm biodiversity compared to non-organic farms, and a meta-analysis by Bengtsson *et al.* (2005) listed just eight earthworm/organics studies (both overlooking Blakemore, 2000a) but noted that higher SOM correlated with increased worms. Although increase of earthworm under organic management (or decrease under chemical farming) is empirically observed as a causal or concomitant effect (e.g. Blakemore, 2000a, 2016b; Mäder *et al.*, 2002; and Fig. 1), the current author is aware of only one study that has reported a direct link between adding organic matter and natural increase in population of field earthworms. Australian vermicompost trials by Buckerfield & Webster (1996) demonstrated that Barossa Valley vineyards benefited from the applications of organic mulches under-vine rather than 'normal practices' of keeping the soil bare. They recorded higher soil moisture (34%), significant grape yield increases (46%) plus increased earthworm density (155%). Howard (1945) had already reported on such issues in vineyards and other sites, but further research along similar lines is required as abundant resident populations of earthworms can be indication of healthy soil sustainability whereas if earthworms decline, as with canaries in a mine, it may portend catastrophic ecosystem collapse, or possibly reversed ecological succession.

Studies by the author (Blakemore, 1994, 2000a; 2016b) found earthworm proliferations of +57-122% under adjacent organic vs. conventional fields related to improved soil characteristics and enhanced yields of +12-80% in winter wheat (Haughley in UK), pasture (Samford in Australia), tropical paddy rice & broadacre sugarcane (in Philippines). Alternatively these data may be interpreted as earthworm decline under intensive cultivation (as in Fig. 1 above). Fig. 8 summarizes Haughley results.

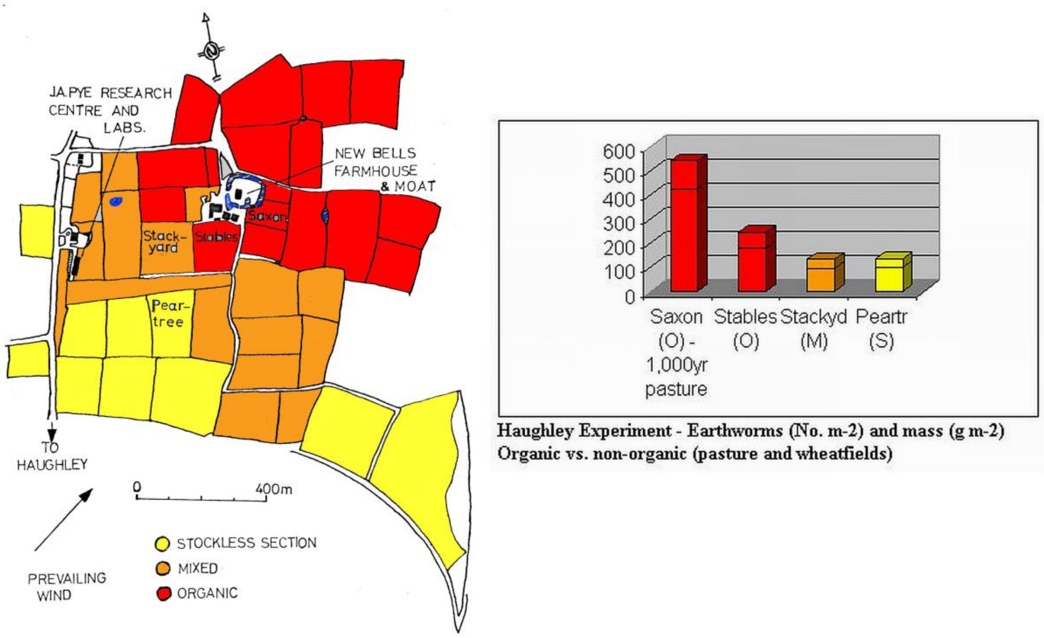


Figure 8. Haughley experimental farm in 1980/1 with earthworms highest in pasture, then organic arable (O = organic) and lowest in arable (M = mixed; S = stockless agrichemical). Earthworms corresponded to yields, H_2O and C levels.

Effects of organic farming/earthworms on soil moisture and soil temperature

It is pertinent that one consequence of variable climate is the unreliability of rainfall and thus an distinct advantage of organically farmed soils is their intrinsic ability to hold more moisture due in part to the increased channels for infiltration and spongy texture acquired from the activities of resident earthworms. Such differences in moisture may help carry a crop through a drought (e.g. Lotter *et al.* , 2003; Rodale, 2015) and help reduce critical delays in planting or harvesting. Increases in soil moisture retention and productivity adds profit from reduced irrigation and premium prices for organic produce without the substantial public fund subsidies afforded to conventional farming. Benefits of organic conversion in the volatile market of carbon credits and offsets to farmers in both developing and developed world are other important considerations.

An often overlooked yet highly important factor is the actual temperature of topsoils. At Haughley in mid-winter the darker organic soil (Munsell: Dark 10YR 2/2) was 1-2°C warmer compared to non-organic soils in immediately adjacent fields (Blakemore, 1981; 2000a); this is another potential benefit to crops and farmers as it may allow plant growth earlier in Spring. As with the higher moisture levels, the differences in physical characteristics attributed to earthworm activities can be accounted for by the soil structural fluffiness providing better thermal insulation, and by an obvious albedo absorptive characteristics of darker organic soil when exposed to sunlight. Thus it may be demonstrated that earthworms effectively alter actual temperature as well as improving moisture levels of soils. This is another area meriting further research.

Effects of organic farming on earthworm species biodiversity

Permaculture and different models of organic farming in essence aim to "*feed earthworms*" and build topsoil (e.g., Howard, 1940; Balfour, 1977; Mollison, 1988), based on Darwin's (1881) earlier determination that humus was formed through the action of diverse earthworms. Currently 7,000 megadrile are scientifically described but their ecology mostly remains a mystery except for only a few dozen species (Lee, 1985; Blakemore, 1994; 2012a). And, rather than just "*two to five*" mainly lumbricid species per site from habitats around the world summarized in Lee 1985: tab. 7), proper eco-taxonomic studies by the author have revealed much higher diversity from mixed or organic farms with averaging about 13 species (Blakemore, 2016b). At Y Plas gardens in Wales a dozen lumbricids were identified in one day (Blakemore, 2013). Other examples are 23 earthworm species on ca. 100 ha farm at Samford near Brisbane, and about the same number recorded from Lake Pedder in Tasmania, from "Satoyama" surrounding Lake Biwa in Japan (Blakemore, 1994; 2000b; 2010) and 23 species identified from two organic farms in the Philippines (Blakemore, 2016a, b). The latter studies also reported microbial diversity in organically farmed soils and vermicomposts.

Rather than field-worker worms, certain earthworm species are more familiar as specialist producers of enriched vermicompost fertilizer sourced from almost any organic residue for use as a natural replacement to artificial chemicals (e.g., Lee, 1985; Blakemore, 2015). Vermicomposting returns organic matter whilst removing farmers' 'waste' disposal problems (with manure and vegetable residues often freely supplied) plus synthetic fertilizer costs/debts and downstream pollution are eliminated.

An earthworm species' many individual contributions may seem insignificant to organic soil formation globally but, as Darwin (1881) explained, such small biological changes in time have enormous cumulative effects. Thus earthworms may be crucial to both food production and carbon sequestration, whilst also helping store soil water and conserving or enhancing on-farm and surrounding natural biodiversity.

CONCLUSIONS

Lal (2010) addresses the imminent 'trilemma' of climate change, food insecurity for nine billion population, and meeting high energy demand. He advocates minimizing environmental costs by building organic soils and reducing fossil-fuel-based input of conventional agriculture thus increasing crop yields (he shows positive relation of yield to SOM) with an estimate that +10% soil carbon is achievable over the next 100 yrs. This is a potential sink of about 100 ppm atmospheric C reducing the current 400 ppm to near pre-industrial levels of ca. 280 ppm. The present report concurs with his findings; however, unlike Lal, here I also consider earthworm biodiversity and more rapid rates of topsoil restoration with Permaculture methods as are briefly noted below.

In this review and other studies it is clear that earthworms and fertile soils are synonymous. Techniques to increase soil carbon, moisture retention and resident earthworm populations differ in different climates but may include the management regimes described for the farms in the various studies reviewed herein. Albrecht (1938) was visionary in discussing the risks and solutions for restoring SOM and his work merits re-evaluation under the prevailing socio-political and environmental issues.

The carbon sink concept of the Kyoto Protocol (Article 3.4) and its COP15 and COP21/22 (2015/2016) successors may therefore be partly accomplished most efficiently by conversion to organic production, as indeed advocated by the IUCN (2015) and the "4 per 1000 Initiative" (http://4p1000.org/). Conant *et al.* (2001) reported most rapid accumulation of C (1.01-3.04 t ha^{-1} yr^{-1}) was from converting cultivated lands to grasslands, adding earthworms or improving grass species. However food production also requires crop security and, since the only way to remove CO_2 from the atmosphere is via plants, therefore more varieties of both crops and pastures are required with longer growing seasons and (as at Haughley reported by Blakemore, 2000) with regular crop rotations.

The limiting factors to plant growth, given abundant sunlight and CO_2, are soil nutrients and water, both of which can be maintained in agricultural/horticultural and pastoral soils by recycling all organic matter as compost, or better yet as vermicompost, and by encouraging earthworms. Since there is often an oversupply of N, it is most likely H_2O is the next most limiting factor. This is increased by adopting management such as Yeoman's Keyline farming as advocated by Permaculture, (Mollison, 1988; Yeoman, 2015), Japanese Satoyama, or other natural and simple methods to encourage earthworms. Geoff Lawton (pers. com.) has demonstrated rapidly restoration of degraded soils by transforming Jordanian desert into an oasis in just four years with Permaculture practices ("*Greening the Desert*", Ecofilms, 2014). Perhaps the most significant finding from the author's concurrent studies is confirmation that application of vermicomposts and/or farm-yard manure enhances field earthworms and their working throughout the organic soil profile increases rainfed water storage whilst raiding both crop yield and carbon storage in pastures and in each of three study sites for three major crops of wheat, rice and sugarcane (Blakemore, 2016b).

An agroecological or permaculture approach offers food safety and lessens severity of unpredictable ecological, economic, and social consequences of global climate change in line with agenda of the COP meetings (De Schutter, 2010; Ruitenberg, 2015; COP21, 2015). Thus a simple organic solution may solve the trilemma problems of CO_2, organic 'waste' pollution, and perhaps most importantly, an accelerating rate of human-induced species extinction threatening our fundamental biodiversity heritage (Rockström *et al.*, 2009). Applying 'environmental triage' and aiming primarily to reduce rates of species extinction would incidentally resolve many other major issues; simply giving more consideration to the earthworms would be a suitable and justifiable starting point towards this goal, as indeed Charles Darwin (1881) already directed us.

The Paris COP21 Climate Change Policy meeting in December, 2015 formally allocated 4% of global GDP towards mitigation. It is hoped some funding will be directed at earthworm/organic research for a more enlightened and permanent system of agriculture based upon our shared natural heritage and an appropriately well-designed, safe future.

REFERENCES

ABC, 2012. Australian Broadcast Company's C isotopes article. (Accessed on 12 September, 2015); http://www.abc.net.au/science/articles/2012/03/14/3452867.htm.

Albrecht W.A., 1938. Loss of Soil Organic Matter and Its Restoration. U.S. Department of Agriculture, Soils and Men, Yearbook of Agriculture. Pp. 347-360. (http://www.soilandhealth.org/01aglibrary/010120albrecht.usdayrbk/lsom.html).

Asner G.P., Scurlock J.M.O., Hicke J.A., 2003. Global synthesis of leaf area index observations: implications for ecological and remote sensing studies. Global Ecology & Biogeography. 12: 191-205. (http://www2.geog.ucl.ac.uk/~mdisney/teaching/teachingNEW/GMES/LAI_GLOBAL_RS.pdf).

Badgley C., Moghtader J., Quintero E., Zakem E., Chappell M.J., Aviles-Vazquez K., Samulon A., Perfecto I., 2007. Organic agriculture and the global food supply. Renewable Agriculture and Food Systems. 22(2): 86–108.

Baldock J., Broos K., 2008. Can we build-up carbon and can we sell it? Australian Grain. May-June, 2008. 2(8): 4-9.

Balfour E.B., 1959. Introduction to "Harnessing the Earthworm" by Dr. Thomas J. Barrett, Humphries, 1947; Wedgewood Press, Boston. 1959. (http://journeytoforever.org/farm_library/oliver/balfour_intro.html).

Balfour E.B., 1977. Towards a Sustainable Agriculture – The Living Soil. Address to an International Federation of Organic Agricultural Movements (IFOAM) conference in Switzerland. (Accessed 15th September, 2015); http://www.soilandhealth.org/01aglibrary/010116Balfourspeech.html.

Batjes N.H., 1996. Total carbon and nitrogen in the soils of the world. European Journal of Soil Science. 47: 151-163. https://library.wur.nl/isric/fulltext/isricu_t47d6414d_001.pdf.

Bengtsson J. Ahnstrom J., Weibull A-C., 2005. The effects of organic agriculture on biodiversity and abundance: a meta-analysis. Journal of Applied Ecology. 42(2): 261-269. http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2664.2005.01005.x/pdf.

Birkhofer K., Bezemer T.M., Bloem J., Bonkowski M., Christensen S., Dubois D., Ekelund F., Flieszbach A., Gunst L., Hedlund K., Mäder P., Mikola J., Robin C., Setala H., Tatin-Froux F., Van der Putten W.H,, Scheu S. 2008. Long-term organic farming fosters below and aboveground biota: Implications for soil quality, biological control and productivity. Soil Biology and Biochemistry. 40(9): 2297-2308.

Black D., Thunell R., Wejnert K., Astor Y., 2011. Carbon isotope composition of Caribbean Sea surface waters: Response to the uptake of anthropogenic CO2. Geophysical Research Letters. 38: L16609, doi:10.1029/2011GL048538.

Blakemore R.J., 1981. Ecology of earthworms under different fertilizer regimes in agriculture. Unpub. BSc. Hons. Thesis, Westminster Uni., 801/1/22. Pp. 93.

Blakemore R.J., 1994. Earthworms of south-east Queensland and their agronomic potential in brigalow soils. Unpub. PhD. Thesis, University of Queensland. Pp. 605. http://www.annelida.net/earthworm/PhD%20Thesis/PhDThesis.DOC.

Blakemore R.J. 2000a. Ecology of earthworms under the 'Haughley experiment' of organic and conventional management regimes. Biological Agriculture and Horticulture. 18: 141—159. DOI: 10.1080/01448765.2000.9754876. (Available online: www.annelida.net/earthworm/Haughley/Haughley.doc).

Blakemore R.J., 2000b. Taxonomic and conservation status of earthworms from Lake Pedder, Tasmania Wilderness World Heritage Area. Records of the Queen Victoria Museum. No. 109: 1-36.

Blakemore, R.J., 2010a. Unravelling some Kinki worms (Annelida:Oligochaeta:Megadrili:Megascolecidae) Part II. *Opuscula Zoologica*. 42(2): 191-206. [Online: http://opuscula.elte.hu/PDF/Tomus41_2/3_%20Blakemore_Kiniki2.pdf].

Blakemore R.J. 2010b. Wonder Worm to the Rescue. (Accessed on 12 September, 2015); United Nations University (UNU). Our World 2.0. 2010 website - http://ourworld.unu.edu/en/wonder-worm-to-the-rescue.

Blakemore R.J., 2012a. Cosmopolitan Earthworms – an Eco-Taxonomic Guide to the Peregrine Species of the World. V[th] Edition. VermEcology, Yokohama. Pp. 950.

Blakemore R.J. 2012b. Call for a Census of Soil Invertebrates (CoSI). Zoology in the Middle East, Supplementum. 4: 163-170. [http://www.kasparek-verlag.de/PDF%20Abstracts/ZME%20SUPP4%20Abstracts/163-170%20Blakemore%20-%20census.pdf].

Blakemore R.J. 2013. *Megascolex (Perichaeta) diffringens* Baird, 1869 and *Pheretima pingi* Stephenson, 1925 types compared to the *Amynthas corticis* (Kinberg, 1867) and *A. carnosus* (Goto & Hatai, 1899) species-groups (Oligochaeta: Megadrilacea: Megascolecidae). Journal of Species Research. 2(2): 99-126. [http://ocean.kisti.re.kr/downfile/volume/nibr/JOSRB5/2013/v2n2/JOSRB5_2013_v2n2_99.pdf].

Blakemore R,J., 2015. Eco-taxonomy of iconic vermicomposter - the 'African Nightcrawler' earthworm, *Eudrilus eugeniae* (Kinberg, 1867). African Invertebrates. 56(3a): 527-548. [Online 25[th] Nov., 2015: http://africaninvertebrates.org/ojs/index.php/AI/article/view/395].

Blakemore, R.J., 2016a. Darwin's earthworms (Annelida, Oligochaeta, Megadrilacea) with review of cosmopolitan *Metaphire peguana*–species group from Philippines. Opuscula Zoologica. 47: 99-99. [http://opuscula.elte.hu/PDF/Tomus47_1/Op_Blakemore_Darwins_%20Earthworms.pdf].

Blakemore, R.J., 2016b. EARTHWORMS IN ORGANIC FIELDS RESTORE SOM & H_2O AND FIX CO_2. VermEcology Occasional Papers (Current). Online 1[st] Sept., 2006 https://veop.files.wordpress.com/2016/09/vvv-ii.pdf.

Blouin M., Zuily-Fodil Y., Pham-Thi A.T., Laffray D., Reversat G., Pando A., Tondoh J., Lavelle P., 2005. Belowground organism activities affect plant aboveground phenotype, inducing plant tolerance to parasites. Ecology Letters. 8: 202–208.

Böhm F., Haase-Schramm A., Eisenhauer A., Dullo W-C., Joachimski M.M., Lehnert H., Reitner J., 2002. Evidence for preindustrial variations in the marine surface water carbonate system from coralline sponges, Geochemistry, Geophysics, Geosystems. 3(3): 10.1029/2001GC000264. ftp://ftp.ncdc.noaa.gov/pub/data/paleo/coral/caribbean/pedro_bank_2002.txt.

Bohn H.L., 1976. Estimate of organic carbon in world soils. Soil Science Society of America Journal. 40: 468-470.

Buckerfield J.C., Webster K.A., 1996. Earthworms, mulching, soil moisture and grape yields. The Australian and New Zealand Wine Industry Journal. 11(1): 47-53.

Buringh P., 1984. Organic Carbon in Soils of the World. In: The Role of Terrestrial Vegetation in the Global Carbon Cycle. G.M. Woodwell (ed.). SCOPE, John Wiley & Sons. Pp. 91-109. (http://dge.stanford.edu/SCOPE/SCOPE_23/SCOPE_23_3.1_chapter3_91-109.pdf).

Campbell A., 2008. Food, energy, water: conflicting insecurities. Journal of Soil and Water Conservation. 63: 149A–151A.

Carson R., 1963. Silent Spring. Houghton Mifflin.

Carvalhais N., Forkel M., Khomik M., Bellarby J., Jung M., Migliavacca M., Mu M., Saatchi S., Santoro M., Thurner M., Weber U., Ahrens B., Beer C., Cescatti A., Randerson J.T., Reichstein M., 2014. Global covariation of carbon turnover times with climate in terrestrial ecosystems. Nature. 514: 213-217. doi:10.1038/nature13731.

CDIAC, 2015a. Carbon Dioxide Information Analysis for US Department of Energy. (Accessed on 12 September, 2015); website, http://cdiac.ornl.gov/pns/convert.html#2.

CDIAC, 2015b. Carbon Dioxide Information Analysis for US Department of Energy. (Accessed on 12 September, 2015); website, http://cdiac.ornl.gov/GCP/carbonbudget/2014/.

Chan Y., 2008. Increasing soil carbon of agricultural land. NSW DPI Primefact 735. (Accessed on 12 September, 2015); http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/210756/Increasing-soil-organic-carbon.pdf.

Chaboussou F., 1985. Healthy Plants, A New Agricultural Revolution, Jon Carpenter, Charlbury, UK. (English 2004 translation).

CIA, 2015a. CIA Factbook. (Accessed on 12 September, 2015); http://en.wikipedia.org/wiki/List_of_countries_by_GDP_sector_composition.

C-MASC, 2015. Carbon Management and Sequestration Center online resource. (Accessed 12 September, 2015); http://cmasc.osu.edu/pageview2/Home.htm .

Comis D., 2002. Glomalin: Hiding place of a third of the World's stored soil carbon. Agricultural Research. September, 2002: 4-7. (http://www.ars.usda.gov/is/ar/archive/sep02/soil0902.htm).

Conant R.T., Paustian K., Elliott E.T., 2001. Grassland management and conversion into grassland: effects on soil carbon. Ecological Applications. 11: 343-355. (http://onlinelibrary.wiley.com/doi/10.1890/1051-0761(2001)011%5b0343:GMACIG%5d2.0.CO%3b2/epdf).

COP21, 2015. COP Climate Change Policy meeting. (Accessed on 12 September, 2015); http://www.cop21paris.org/about/cop21.

Crawford J., 2012. What If the World's Soil Runs Out. Time. Dec. 14. (http://world.time.com/2012/12/14/what-if-the-worlds-soil-runs-out/#comments).

Darwin C.R., 1881. The formation of vegetable mould, through the action of worms, with observations on their habits. John Murray, London.

De Schutter O., 2010. Agroecology and the right to food. Report to the UN General Assembly. A/HRC/16/49. (Accessed 12 September, 2015); http://civileats.com/wp-content/uploads/2011/03/20110308_UN_agroecology_report.pdf.

DoE, 2008. Carbon Cycling and Biosequestration: Integrating Biology and Climate Through Systems Science; Report from the March 2008 Workshop, DOE/SC-108, U.S. Department of Energy Office of Science. (Accessed 12 September, 2015); genomicscience.energy.gov/carboncycle/.

Ecofilms, 2014. Geoff Lawton's "From Desert to Oasis in 4 Years (Jordan)". (Accessed 12 September, 2015); Online report: http://permaculturenews.org/2014/02/01/desert-oasis-4-years-jordan/.

ELD, (2015). Economics of Land Degradation Initiative (2015). The value of land: Prosperous lands and positive rewards through sustainable land management. http://eld-initiative.org/fileadmin/pdf/ELD-main-report_05_web_72dpi.pdf;

summarized here: https://hq290.infusionsoft.com/app/linkClick/963/cb6749440a8c17cd/506997/57bd014d61063c74.
El-Shamei Z.S., Gab-Alla A.A., Shatta A.A., Moussa E.A., Rayan A.M., 2012. Histopathological changes in some organs of male rats fed on genetically modified corn (Ajeeb YG). Journal of American Science. 8(10): 684–696.
Edwards C.A., 2009. Can earthworms harm the planet? Biocycle. December, 2009: 53-54.
FAO, 1998. Food Balance Sheets; 1998. (Accessed on 12 September, 2015); http://armanncorn:98ivysub@faostat.fao.org/lim...ap.pl? (September, 24, 2000).
FAO, 1991. The State of Food and Agriculture; 1990. FAO Agriculture Series No. 23. FAO, Rome. 1991.
FAO, 2011. Save and Grow: A policymaker's guide to the sustainable intensification of smallholder crop production. Pp 112. (http://www.fao.org/ag/save-and-grow/en/2/index.html).
FAO, 2013. Food and Agriculture Organization. Global Yields: 2013. (Accessed on 12 September, 2015); http://www.fao.org/docrep/005/y4137e/y4137e03b.htm#64
FAO, 2014a. Water withdrawal by sector, around 2007. (Accessed on 12 September, 2015); http://www.fao.org/nr/water/aquastat/tables/WorldData-Withdrawal_eng.pdf.
FAO, 2014b. Food and Agriculture Organization. Soil Conservation and Agriculture Report. (Accessed on 12 September, 2015); http://www.fao.org/soils-portal/soil-biodiversity/soil-conservation-and-agriculture/jp/.
FAO, 2014c. Food and Agriculture Organization. Benefits of Biodiversity Report. (Accessed on 12 September, 2015); www.fao.org/fileadmin/templates/soilbiodiversity/Drawings/economic_benefits_of_biodiversity.pdf.
FAO, 2015. Status of the World's Soil Resources. Technical Summary. (www.fao.org/documents/card/en/c/39bc9f2b-7493-4ab6-b024-feeaf49d4d01/).
FAO, 2015. Online report on organic yields; 2015. (Accessed on 12 September, 2015); http://www.fao.org/organicag/oa-faq/oa-faq7/en/.
FAOSTAT, 2013. FAO Statistics Report 2013. (Accessed on 12 September, 2015); http://faostat.fao.org/site/368/default.aspx#ancor.
FAOSTAT, 2015. FAO Statistics Home; 2015. (Accessed on 12 September, 2015); http://faostat3.fao.org/home/E.
FIBL, 2015. Research Institute of Organic Agriculture (FiBL); 2015. (Accessed on 12 September, 2015); website. www.fibl.org.
FiBL-IFOAM, 2014. Surveys and other sources reported on Wikipedia. (Accessed on 12 September, 2015); http://en.wikipedia.org/wiki/Organic_farming.
Fliessbach A., Imhof D., Brunner T., Wüthrich C., 1999. Tiefenverteilung und zeitliche Dynamik der mikrobiellen Biomasse in biologisch und konventionell bewirtschafteten Böden. Regio Basiliensis. 3: 253–263.
Fliessbach A., Oberholzer HR, Gunst L, Mäder P., 2007. Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming. Agricultural Ecosystems and Environment. 118: 273–284

(http://www.sciencedirect.com/science/article/pii/S0167880906001794).

Gattinger A., Mulli A., Hani M., Oehen B., Stolze M., Niggli U., 2012. Soil carbon sequestration of organic crop and livestock systems and potential for accreditation by carbon markets. (Food and Agriculture Organization of the United Nations (FAO), Natural Resources Management and Environment Department, 2011). (Accessed 12 Sept., 2015); http://orgprints.org/21773/.

Gaupp-Berghausen M., Hofer M., Rewald B., Zaller J.G., 2015. Glyphosate-based herbicides reduce the activity and reproduction of earthworms and lead to increased soil nutrient concentrations. Scientific Reports. 5: 12886. (http://www.nature.com/articles/srep12886).

Giampietro M., Pimentel D., 1993. The Tightening Conflict: Population, Energy Use, and the Ecology of Agriculture. Negative Population Growth, The NPG Forum: 1-7. (Accessed on 12 September, 2015); http://dieoff.org/page69.htm; www.ishmael.org/Education/Science/tightening_conflict.cfm.

GCP, 2015. Global Carbon Project (2015) Carbon budget and trends 2014. [www.globalcarbonproject.org/carbonbudget] published on 8 May 2015 especially Le Quéré *et al.* (2014: tab. 10). (Accessed on 12 September, 2015); Summarized online: http://www.globalcarbonproject.org/carbonbudget/14/hl-full.htm#cumulative; http://www.globalcarbonproject.org/index.htm.

GLASNOD, 1991. Global Land Assessment Report; 1991. (Accessed on 12 September, 2015); www.isric.org/projects/global-assessment-human-induced-soil-degradation-glasod.

Green M., Maynard R., 2006. The employment benefits of organic farming. In: Aspects of Applied Biology 79, What will organic farming deliver? Pp. 51-55.

Halweil, B., 2006. Can organic farming feed us all? World Watch. 19(3):19-24. (Online: http://www.worldwatch.org/node/4060).

Hammond B., Dudek R., Lemen J., Nemeth M., 2004. Results of a 13 week safety assurance study with rats fed grain from glyphosate tolerant corn. Food Chemical Toxicology. 42: 1003–1014. (bruce.g.hammond@monsanto.com; www. www.ncbi.nlm.nih.gov/pubmed/15110110).

Harper R.J., Tibbett M., 2013. The hidden organic carbon in deep mineral soils. Plant and Soil. 368 (1-2): 641-648. (http://link.springer.com/article/10.1007%2Fs11104-013-1600-9).

Henriksen C.B., Hussey K., Holm P.E., 2011. Exploiting soil-management strategies for climate mitigation in the European Union: maximizing "win–win" solutions across policy regimes. Ecology and Society. 16(4): art. 22. http://dx.doi.org/10.5751/ES-04176-160422. [http://www.ecologyandsociety.org/vol16/iss4/art22/.

Hodson M., 2009. Darwin's humble earthworm. (Accessed on 12 September, 2015); Planet Earth Online. 30 January, 2009. http://planetearth.nerc.ac.uk/features/story.aspx?id=306.

Howard A., 1940. An Agricultural Testament. London: Oxford University Press. Pp. 253.

Howard A., 1945. Introduction to "*The Formation of Vegetable Mould through the Action of Worms with Observations on their Habits*" by Charles Darwin, John

Murray, London, 1881; Faber and Faber, London, 1945. [Online http://journeytoforever.org/farm_library/oliver/howard_intro.html].

IAASTD, 2008. UNEP online report; accessed 4/2/2015. www.unep.org/dewa/Assessments/Ecosystems/IAASTD/tabid/105853/Default.aspx.

IAEES, 2015. Real-time data of environmental change; 2015. International Academy of Ecology and Environmental Sciences. (Accessed 12 September, 2015); Online data: http://www.iaees.org/environdata/enframe.asp?xuhao=2.

INCHEM, 2015. NITRATE. First draft prepared by Laboratory for Toxicology, National Institute of Public Health & Environmental Protection, Bilthoven, Netherlands; 2015. (Accessed 12 Sept., 2015); http://www.inchem.org/documents/jecfa/jecmono/v35je14.htm.

IPCC, 2007. Fourth Assessment Report (AR4). Climate Change 2007: Synthesis Reports. (Accessed 12 Sept., 2015); http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm.

IPCC, 2014. IPCC's Fifth Assessment Report AR5, 2014. (Accessed 12 Sept., 2015); online: http://www.ipcc.ch/report/ar5/.

I-SIS, 2015. Special Report: Banishing Glyphosate. (Accessed 12 Sept., 2015); http://www.i-sis.org.uk/Banishing_Glyphosate.php .

IUCN, 2015. Land degradation and climate change. Brief Reports. November, 2015. [www.iucn.org/sites/dev/files/import/downloads/land_degradation_issues_brief_cop21_031215.pdf ; http://cmsdata.iucn.org/downloads/tech_brief_land_degradation_neutrality.pdf - Note: their data (from UNCCD) is similar but differs from that presented in this report regarding total carbon budgets)].

Jackson R.B., Mooney H.A., Schulze E-D., 1997. A global budget for fine root biomass, surface area, and nutrient contents. Proceedings of the National Academy of Sciences, USA. 94: 7362-7366. (http://sites.biology.duke.edu/jackson/PNAS97.pdf).

Jayasumana C., Paranagama P., Agampodi S., Wijewardane C., Gunatilake S., Siribaddana S., 2005. Drinking well water and occupational exposure to herbicides is associated with chronic kidney disease, in Padavi-Sripura, Sri Lanka. Environmental Health. 14: 6 doi:10.1186/1476-069X-14-6.

Jobbagy E.G., Jackson R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecological Applications. 10: 423– 436. (http://onlinelibrary.wiley.com/doi/10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2/full).

Kretzschmar A., 1982. Description des galeries de vers de terre et variations saisonnières des réseaux (observations en conditions naturelles). Revue of Ecology and Biology of Soils. 19: 579–591 (1982).

Kovda V.A., 1974. Biosphere, soils and their utilization. 10th International Congress Soil Science. Moscow.

Krüger M., Schledorn P., Schrödl W., Hoppe H.W., Lutz W., Shehata A.A., 2014. Detection of Glyphosate Residues in Animals and Humans. Environmental & Analytical Toxicology. 4(2): 1-5. (http://dx.doi.org/10.4172/2161-0525.1000210).

Lal R., 2004. Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. Science. 304 (5677): 1623–1627. Bibcode:2004Sci...304.1623L. doi:10.1126/science.1097396. PMID 15192216.

Lal R., 2008. Sequestration of atmospheric CO_2 in global carbon pools. Energy and Environmental Science. 1(1): 86–100. doi:10.1039/b809492f.

Lal R., 2010. Managing soils for a warming earth in a food-insecure and energy-starved world. Journal of Plant Nutrition and Soil Science. 173(1): 4–15.

Lal R, Bruce J.B., 1999. The potential of world cropland soils to sequester C and mitigate the greenhouse effect. Environmental Science & Policy. 2: 177-185.

Lal R., Follett R.F., 2009. Soil carbon sequestration and green-house effect, 2nd edn. Soil Science Society of America, Madison, WI.

Lappé A. 2014. 5 Questions for an International Organics Expert: IFOAM's Andre Leu. (Accessed on 12 September, 2015); Online article by Anna Lappé at: Civil Eats . http://civileats.com/2014/11/13/5-questions-for-an-international-organics-expert-ifoams-andre-leu/#sthash.ui76b7O2.dpuf.

Leifeld J., Fuhrer J., 2010. Organic Farming and Soil Carbon Sequestration: What Do We Really Know About the Benefits? Ambio. 39(8): 585–599. (http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3357676/).

Lee K.E., 1985.Earthworms, their ecology and relationships with soils and land use. Academic Press. New York, NY.

Leu A., 2007. Organics and Soil Carbon: Increasing soil carbon, crop productivity and farm profitability. Managing the Carbon Cycle Katanning Workshop 21-22, March, 2007. (Accessed on 12 September, 2015); Online: www.amazingcarbon.com/Leu%20-%20Organics%20and%20soil%20carbon.pdf.

Loening U., 2004, in Chaboussou, 2004 translation. Healthy Plants, A New Agricultural Revolution, Jon Carpenter, Charlbury, UK.

Lotter D.W., Seidel R., Liebhardt W., 2003. The performance of organic and conventional cropping systems in an extreme climate year. American Journal of Alternative Agriculture. Volume18, Number 3: 146-154.

Lubbers I.M., van Groenigen K.J., Fonte S.J., Six J., Brussaard L., van Groenigen J.W., 2013. Greenhouse gas emissions from soils increased by earthworms. Nature Climate Change. 3: 187–194.

Mäder P., Fließbach A., Dubois D., Gunst L., Fried P., Niggli U., 2002. Soil Fertility and Biodiversity in Organic Farming. Science. 296: 1694-1697. (http://www.sciencemag.org/content/296/5573/1694.full).

Maynard R., Green M., 2006. Organic works - Providing more jobs through organic farming and local food supply. Soil Association, London. (Accessed on 12 September, 2015); Available from: www.soilassociation.org.

McKie R., 2013. From fertiliser to Zyklon B: 100 years of the scientific discovery that brought life and death. The Observer; 2013. (Accessed on 12 September, 2015); Online: http://www.theguardian.com/science/2013/nov/03/fritz-haber-fertiliser-ammonia-centenary.

MEA, 2005. Millenium Environmental Assessment. (Accessed on 12 September, 2015);

http://www.millenniumassessment.org/en/index.html.
Mollison B.C., 1988. Permaculture: A Designers' Manual. Tagari Publications, Tasmania.
NASA, 2011. National Aeronautics and Space Administration Earth Observatory. (Accessed on 12 September, 2015); http://earthobservatory.nasa.gov/Features/CarbonCycle/.
Paull J., 2007. Trophobiosis Theory: A Pest Starves on a Healthy Plant. ELEMENTALS ~ Journal of Bio-Dynamics Tasmania. 88: 24-28. (Archived at: http://orgprints.org/12894/1/12894.pdf).
Pfiffner L., Balmer O., 2011. Organic agriculture and biodiversity. FIBL, Frankfurt, Feb. 2011. 1548: 1-4. (Online: https://shop.fibl.org/fileadmin/documents/shop/1548-biodiversity.pdf).
Pimentel D., 2005. Environmental and economic costs of the application of pesticides primarily in the United States. Environment, Development, and Sustainability. 7: 229-252.
Pimentel D., 2006. Soil Erosion: A Food and Environmental Threat. Environment, Development and Sustainability. 8(1): 119-137.
Pimentel D., Giampietro M., 2008. Reducing energy inputs in the US food System. Human Ecology. 36, 459-471.
Pimentel, D. & Burgess, M., 2013. Soil erosion threatens food production. Agriculture. 3(3): 443-463. doi:10.3390/agriculture3030443 (online: http://www.mdpi.com/2077-0472/3/3/443/htm#B8-agriculture-03-00443).
Pimentel D., Berardi G., Fast S., 1983. Energy efficiency of farming systems: organic and conventional agriculture. Agriculture, Ecosystems and Environment. 9: 359-372.
Pimentel D., Hepperly P., Hanson J., Seidel R., 2005. Organic and Conventional Farming Systems: Environmental and Economic Issues. Environmental Biology. (Accessed on 12 September, 2015); http://dspace.library.cornell.edu/bitstream/1813/2101/1/pimentel_report_05-1.pdf
Ponisio, L.C., M'Gonigle, L.K., Mace, K. Palomino, J., de Valpine, P., Kremen, C., 2014. Diversification practices reduce organic to conventional yield gap. *Proceedings of the Royal Society: B.* 282: 20141396 (pdf).
Pusztai A., Bardocz S., Ewen S.W., 2003. Genetically modified foods: potential human health effects. In: J.P.F. D'Mello (Ed.), Food safety: contaminants and toxins, CABI Publishing, Wallingford.
Racelis E.L., Caradang W.M., Lasco R.D., Racelis D.A., Castillo A.S.A., Pulhin J.M., 2008. Assessing the Carbon Budgets of Large Leaf Mahogany (*Swietenia macrophylla* King) and Dipterocarp Plantations in the Mt. Makiling Forest Reserve, Philippines. Journal of Environmental Science and Management. 11: 40-55.
Rockström J., Steffen W., Noone K., Persson Å., Chapin III F.S., Lambin E.F., Lenton T.M., Scheffer M., Folke C., Schellnhuber H.J., Nykvist B., de Wit C.A., Hughes T., van der Leeuw S., Rodhe H., Sörlin S., Snyder P.K., Costanza R., Svedin U., Falkenmark M., Karlberg L., Corell R.W., Fabry V.J., Hansen J., Walker B., Liverman D., Richardson K., Crutzen P., Foley J.A., 2009. A safe operating space for humanity. Nature. 461: 472–475. (doi:10.1038/461472a ;

http://steadystate.org/wp-content/uploads/2009/12/Rockstrom_Nature_Boundaries.pdf).
Rodale Institute, 2015. "The Farming Systems Trial: Celebrating 40 years"; 2015. (Accessed on 12 September, 2015); Brochure available online: http://rodaleinstitute.org/assets/FSTbooklet.pdf ; http://66.147.244.123/~rodalein/wp-content/uploads/2012/12/FSTbookletFINAL.pdf .
Ruitenberg R., 2015. (Accessed on 12 September, 2015); Bloomberg news online report; 2015. (Accessed on 12 September, 2015); http://www.bloomberg.com/news/articles/2015-07-28/france-backs-soil-carbon-plan-ahead-of-climate-summit-le-foll .
Santadino M., Coviella C., Momo F., 2014. Glyphosate Sublethal Effects on the Population Dynamics of the Earthworm *Eisenia fetida* (Savigny, 1826). Water, Air, & Soil Pollution. 225: 2207.
Séralini G-E., Clair E., Mesnage R., Gress S., Defarge N., Malatesta M., Hennequin D., De Vendômois J.S., 2012. Long term toxicity of a Roundup herbicide and a Roundup-tolerant genetically modified maize. Food and Chemical Toxicology. 50 (11): 4221–4231. doi:10.1016/j.fct.2012.08.005. PMID 22999595. (Redacted - http://www.sciencedirect.com/science/article/pii/S0278691512005637; http://www.sciencedirect.com/science/article/pii/S0278691512005637/pdfft?md5=8ad73ad58506791b42b6a1f945e4229e&pid=1-s2.0-S0278691512005637-main.pdf).
Séralini G-E., Clair E., Mesnage R., Gress S., Defarge N., Malatesta M., Hennequin D., De Vendômois J., 2014. Republished study: long-term toxicity of a Roundup herbicide and a Roundup-tolerant genetically modified maize. Environmental Sciences Europe. 26 (1): 14. doi:10.1186/s12302-014-0014-5; (online http://scholar.google.co.jp/scholar_url?url=http%3A%2F%2Fwww.biomedcentral.com%2Fcontent%2Fpdf%2Fs12302-014-0014-5.pdf&hl=en&sa=T&oi=ggp&ct=res&cd=0&ei=SfXIVJP8AcqXqgHW0IGgCQ&scisig=AAGBfm1RzIuYQuldgFIe56ur2-qkXomVMg&nossl=1&ws=1104x876).
Seufert V., Ramankutty N., Foley A., 2012. Comparing the yields of organic and conventional agriculture. Nature. 485: 229-232.
Sirinathsinghji E., 2015. A Roundup of Roundup® Reveals Converging Pattern of Toxicity from Farm to Clinic to Laboratory Studies. Health Impact News. The Institute of Science in Society, London; 2015. (Accessed on 12 September, 2015); Available at: http://healthimpactnews.com/2015/a-roundup-of-roundup-reveals-converging-pattern-of-toxicity-from-farm-to-clinic-to-laboratory-studies/#sthash.3dApB0rw.dpuf.
Smil V. 2011. Nitrogen cycle and world food production. *World Agriculture* **2**:9-1.PDF.
Soil Association, 2009. "Soil Carbon and Organic Farming"; 2009. (Accessed on 12 September, 2015); online report: http://www.soilassociation.org/innovativefarming/policyresearch/soilcarbon; http://www.nourishscotland.org/wp-content/uploads/2012/09/sa.pdf .
Stockdill S.M.J., 1992. Effects of introduced earthworms on the productivity of New Zealand pastured. Pedobiologia. 24: 29-35.

Srivastava R., McIlvried H., 2010. Best practices for Terrestrial Sequestration of Carbon Dioxide. NETL, US Department of Energy. November 2010. (Accessed on 12 September, 2015); http://www.netl.doe.gov/File%20Library/Research/Carbon-Storage/Project-Portfolio/BPM_Terrestrial.pdf.

Toffler, A., 1980. *The Third Wave.* Morrow, New York. Pp. 544. [https://archive.org/details/TheThirdWave-Toffler].

UNEP, 2008. UN Environmental Program Report; 2008. (Accessed on 12 September, 2015); http://www.unep-unctad.org/cbtf/publications/UNCTAD_DITC_TED_2007_15.pdf , accessed 4/2/2015.

UNESCO, 2015. UNESCO Report; 2015. (Accessed on 12 September, 2015); http://webworld.unesco.org/water/wwap/facts_figures/.

van Bemmelen J.M., 1891. Ueber die Bestimmungen des Wassers, des Humus, des Schwefels, der in den Colloidalen Silikaten gebunden Kieselsaeuren, des mangans, u.s.w. im Ackerboden. Landwirtschaftliche Versuch Station. 37:279–290.

van Groenigen J.W., Lubbers I.M., Vos H.M.J., Brown G., De Deyn G.B., van Groenigen K.J., 2014. Earthworms increase plant production: a meta-analysis. Scientific Reports. 10.1038/srep06365. (Accessed on 12 September, 2015); http://www.nature.com/srep/2014/140915/srep06365/extref/srep06365-s1.pdf.

Wheeler Q.D., 2004. Taxonomic triage and the poverty of phylogeny. Philosophical Transactions B. 359, (1444): 571-583.

Wheeler Q.D., 2010. What would NASA do? Mission-critical infrastructure for species exploration. Systematics and Biodiversity. 8: 1, 11-15, DOI: 10.1080/14772001003628075.

WHO, 1985. Health hazards from nitrates in drinking water. Copenhagen.

WHO, 2015. IARC Monographs Volume 112: Evaluation of five organophosphate insecticides and herbicides. World Health Organization, 20th March, 2015. (Accessed on 12 September, 2015); http://www.iarc.fr/en/media-centre/iarcnews/pdf/MonographVolume112.pdf.

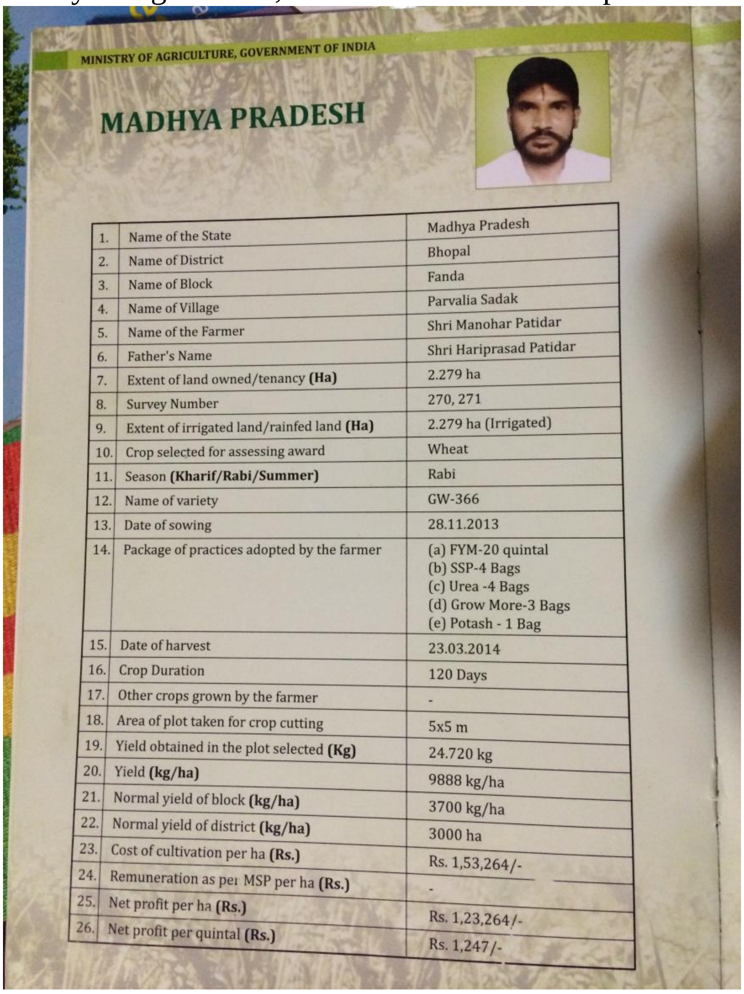
World Bank, 2015. (Accessed on 12 September, 2015); http://data.worldbank.org/.

Yeates G.W., 1991. Impact of historical changes in land use on the soil fauna. New Zealand Journal of Ecology. 15(1): 99-106. [http://newzealandecology.org/nzje/1899.pdf].

Yeoman P.A., 2015. Keyline design online resources. Also accessed on 12 September, 2015; http://www.keyline.com.au/.

Zhang W., Hendrix P., Dame L.E., Burke R.A., Wu J., Neher D.A., Shao J., Li Y., Fu S., 2013. Earthworms facilitate carbon sequestration through unequal amplification of carbon stabilization compared with mineralization. Nature Communications. 4: 2576. doi: 10.1038/ncomms3576.

Appendix. Ministry of Agriculture, Government of India Report for an Organic Farm.



MINISTRY OF AGRICULTURE, GOVERNMENT OF INDIA

MADHYA PRADESH

1.	Name of the State	Madhya Pradesh
2.	Name of District	Bhopal
3.	Name of Block	Fanda
4.	Name of Village	Parvalia Sadak
5.	Name of the Farmer	Shri Manohar Patidar
6.	Father's Name	Shri Hariprasad Patidar
7.	Extent of land owned/tenancy **(Ha)**	2.279 ha
8.	Survey Number	270, 271
9.	Extent of irrigated land/rainfed land **(Ha)**	2.279 ha (Irrigated)
10.	Crop selected for assessing award	Wheat
11.	Season **(Kharif/Rabi/Summer)**	Rabi
12.	Name of variety	GW-366
13.	Date of sowing	28.11.2013
14.	Package of practices adopted by the farmer	(a) FYM-20 quintal (b) SSP-4 Bags (c) Urea -4 Bags (d) Grow More-3 Bags (e) Potash - 1 Bag
15.	Date of harvest	23.03.2014
16.	Crop Duration	120 Days
17.	Other crops grown by the farmer	-
18.	Area of plot taken for crop cutting	5x5 m
19.	Yield obtained in the plot selected **(Kg)**	24.720 kg
20.	Yield **(kg/ha)**	9888 kg/ha
21.	Normal yield of block **(kg/ha)**	3700 kg/ha
22.	Normal yield of district **(kg/ha)**	3000 ha
23.	Cost of cultivation per ha **(Rs.)**	Rs. 1,53,264/-
24.	Remuneration as per MSP per ha **(Rs.)**	-
25.	Net profit per ha **(Rs.)**	Rs. 1,23,264/-
26.	Net profit per quintal **(Rs.)**	Rs. 1,247/-

Fig. 8. Soil Report with FYM = Farm-yard Manure and Indian "quintal" = 100 kg, i.e., 2 t FYM added to field usually as vermicompost; SSP is superphosphate and a "Bag" is 50 kg. Although organic certification often precludes use of synthetic fertilizers, mineral supplements are allowed for composts in certain circumstances.

This Bhopal organic farm that employs non-chemical integrated pest management (IPM) strategies with mechanical or manual weeding, seemingly has a wheat crop >3 times the normal district yield. The farmer, Shri Manohar Patidar (pers. comm. March, 2016), irrigates his fields only twice a year unlike his conventional neighbors who irrigate four times. Soil health reports class as "high" both his Organic C (at 1.14%) and the earthworm counts (Indian Ministry of Agriculture and pers. obs https://vermecology.wordpress.com/2016/05/25/tale-of-two-sitis-vermecology-in-india/). Further studies are required to confirm farm methods, yields and soil/earthworm effects.