A CO_2-ENRICHED WORLD OF WORMS

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"Earthworms," in the words of Edwards (1988), "play a major role in improving and maintaining the fertility, structure, aeration and drainage of agricultural soils." As noted by Sharpley *et al.* (1988), for example, "by ingestion and digestion of plant residue and subsequent egestion of cast material, earthworms can redistribute nutrients in a soil and enhance enzyme activity, thereby increasing plant availability of both soil and plant residue nutrients," as others have also demonstrated (Bertsch *et al.*, 1988; McCabe *et al.*, 1988; Zachmann and Molina, 1988; van Groenigen *et al.*, 2014[1]).

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Likewise, Kemper (1988) describes how "burrows opened to the surface by surface-feeding worms provide drainage for water accumulating on the surface during intense rainfall," noting that "the highly compacted soil surrounding the expanded burrows has low permeability to water which often allows water to flow through these holes for a meter or so before it is absorbed into the surrounding soil." Hall and Dudas (1988) additionally report that the presence of earthworms appears to mitigate the deleterious effects of certain soil toxins; while Logsdon and Lindon (1988) describe a number of other beneficial effects of earthworms, including (1) enhancement of soil aeration, since under wet conditions earthworm channels do not swell shut as many soil cracks do, (2) enhancement of soil water uptake, since roots can explore deeper soil layers by following earthworm channels, and (3) enhancement of nutrient uptake, since earthworm casts and channel walls have a more neutral pH and higher available nutrient level than bulk soil. And, therefore, we truly *do* care about what happens to earthworms as the air's CO_2 content rises, because of the many important services they provide for Earth's plant life.

So how might rising atmospheric CO_2 concentrations impact earthworms? Edwards (1988) says that "the most important factor in maintaining good earthworm populations in agricultural soils is that there be adequate availability of organic matter," while Hendrix *et al.* (1988) and Kladivko (1988) report that greater levels of plant productivity promote greater levels of earthworm activity. Consequently, since the most ubiquitous and powerful effect of atmospheric CO_2 enrichment is its stimulation of plant productivity, which leads to enhanced organic matter delivery to soils, it logically follows that this *aerial fertilization effect* of the ongoing rise in the air's CO_2 content should significantly increase earthworm populations and amplify the many beneficial services they provide for plants.

[1] http://www.co2science.org/articles/V18/jan/a26.php

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Then there's the second most significant and common impact of atmospheric CO_2 enrichment on plants: its *anti-transpirant effect*, whereby elevated levels of atmospheric CO_2 reduce leaf stomatal apertures and slow the rate of evaporative water loss from the vast bulk of Earth's vegetation. Both growth chamber studies and field experiments that have studied this phenomenon provide voluminous evidence that it often leads to increased soil water contents in many terrestrial ecosystems, which is also something earthworms seem to love, i.e., plenty of soil moisture.

In light of these many proven facts, it should not have been surprising that when Zaller and Arnone (1997)[2] fumigated open-top and -bottom chambers they established in a calcareous grassland near Basal, Switzerland with air of either 350 or 600 ppm CO_2 for an entire growing season, they found that the mean annual soil moisture content in the CO_2-enriched chambers was 10% greater than that observed in the ambient-air chambers; and because rates of surface cast production by earthworms are typically positively correlated with soil moisture content, they found that cumulative surface cast production after only one year was 35% greater in the CO_2-enriched chambers than in the control chambers. In addition, because earthworm casts are rich in organic carbon and nitrogen, the cumulative amount of these important nutrients on a per-land-area basis was found to be 28% greater in the CO_2-enriched chambers than it was in the ambient-air chambers. And in a subsequent study of the same grassland, Zaller and Arnone (1999)[3] found that plants growing in close proximity to the earthworm casts produced more biomass than similar plants growing further away from them. What is more, they found that the CO_2-induced *growth stimulation* experienced by the various grasses was also greater for those plants growing nearer the earthworm casts.

The upshot of these various observations is that atmospheric CO_2 enrichment sets in motion a self-enhancing cycle of positive biological phenomena, whereby increases in the air's CO_2 content (1) stimulate plant productivity and (2) reduce plant evaporative water loss, which results in (1) more organic matter entering the soil and (2) a longer soil moisture retention time and/or greater soil water contents, all of which factors lead to the development of larger and more active earthworm populations, which enhance many important soil properties, including fertility, structure, aeration and drainage, which improved properties further enhance the growth of the

[2] http://www.co2science.org/articles/V2/N23/B3.php
[3] http://www.co2science.org/articles/V2/N23/B4.php

plants whose CO_2-induced increase in productivity was the factor that started the whole series of processes on the road to a higher level of activity in the first place, and so on.

But the good news doesn't end there. As Jongmans *et al.* (2003)[4] point out, "the rate of organic matter decomposition can be decreased in worm casts compared to bulk soil aggregates (Martin, 1991; Haynes and Fraser, 1998)." Hence, on the basis of these studies and their own micro-morphological investigation of structural development and organic matter distribution in two calcareous marine loam soils on which pear trees had been grown for 45 years (one of which soils exhibited little to no earthworm activity and one of which exhibited high earthworm activity, due to different levels of heavy metal contamination of the soils as a consequence of the prior use of different amounts of fungicides), they concluded that "earthworms play an important role in the intimate mixing of organic residues and fine mineral soil particles and the formation of organic matter-rich micro-aggregates and can, therefore, contribute to physical protection of organic matter, thereby slowing organic matter turnover and increasing the soil's potential for carbon sequestration." Put more simply, atmospheric CO_2 enrichment that stimulates the activity of earthworms also leads to more -- and more *secure* -- sequestration of carbon in Earth's soils, thereby reducing the potential for CO_2-induced global warming.

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But there's still *more* to the story of CO_2 and worms. In an intriguing research paper published in *Soil Biology & Biochemsitry*, Cole *et al*. (2002)[5] report that "in the peatlands of northern England, which are classified as blanket peat, it has been suggested that the potential effects of global warming on carbon and nutrient dynamics will be related to the activities of dominant soil fauna, and especially enchytraeid worms." In harmony with these ideas, Cole *et al*. say they "hypothesized" that warming would lead to increased enchytraeid worm activity, which would lead to higher grazing pressure on microbes in the soil; and since enchytraeid grazing has been observed to enhance microbial activity (Cole *et al*., 2000), they further hypothesized that more carbon would be liberated in dissolved organic form, "supporting the view that global warming will increase carbon loss from blanket peat ecosystems."

The scientists next describe how they constructed small microcosms from soil and litter they collected near the summit of Great Dun Fell, Cumbria, England. Subsequent to "defaunating" this material by reducing its temperature to -80°C for 24 hours, they thawed and inoculated it with native soil microbes, after which half of the microcosms were incubated in the dark at 12°C and

[4] http://www.co2science.org/articles/V6/N52/B2.php

[5] http://www.co2science.org/articles/V5/N18/COM.php

half at 18°C, the former of which temperatures was approximately equal to mean August soil temperature at a depth of 10 cm at the site of soil collection, while the latter was said by them to be "close to model predictions for soil warming that might result from a doubling of CO_2 in blanket peat environments."

Ten seedlings of an indigenous grass of blanket peat were then transplanted into each of the microcosms, while 100 enchytraeid worms were added to each of half of the mini-ecosystems. These procedures resulted in the creation of four experimental treatments: ambient temperature, ambient temperature + enchytraeid worms, elevated temperature, and elevated temperature + enchytraeid worms. The resulting 48 microcosms -- sufficient to destructively harvest three replicates of each treatment four different times throughout the course of the 64-day experiment -- were arranged in a fully randomized design and maintained at either 12 or 18°C with alternating 12-hour light and dark periods. In addition, throughout the entire course of the study, the microcosms were given distilled water every two days to maintain their original weights.

So what did the researchers find? First of all, and *contrary to their hypothesis*, elevated temperature *reduced* the ability of the enchytraeid worms to enhance the loss of carbon from the microcosms. At the normal ambient temperature, for example, the presence of the worms enhanced dissolved organic carbon (DOC) loss by 16%, while at the elevated temperature expected for a doubling of the air's CO_2 content, the worms had *no effect at all* on DOC. In addition, Cole *et al.* note that "warming may cause drying at the soil surface, forcing enchytraeids to burrow to deeper subsurface horizons." Hence, since the worms are known to have little influence on soil carbon dynamics below a depth of 4 cm (Cole *et al.*, 2000), they concluded that this additional consequence of warming would *further* reduce the ability of enchytraeids to enhance carbon loss from blanket peatlands.

In summarizing their findings, Cole *et al.* remark that "the soil biotic response to warming in this study was negative." That is to say, it was of such a nature that it resulted in a *reduced loss* of carbon to the atmosphere, which would tend to slow the rate of rise of the air's CO_2 content, just as was suggested by the results of the study of Jongmans *et al.* (2003).

Next to contribute to the study of the direct and indirect effects of atmospheric CO_2 enrichment on various types of worms and their subsequent activities that (1) amplify the positive effects of CO_2 on plants and (2) reduce the negative effects of CO_2 on climate, we briefly recount the findings of Yeates *et al.* (2003)[6], who report a number of interesting results they obtained from a season-long FACE study of a 30-year-old New Zealand pasture, where three experimental plots had been maintained at the ambient atmospheric CO_2 concentration of 360 ppm and three others at a concentration of 475 ppm (a CO_2 enhancement of only 32%) for a period of four to five years. This pasture contained about twenty species of plants, including C_3 and C_4 grasses, legumes and forbs; but the scientists' attention was focused more on what happened to the microfauna inhabiting the soil in which the plants grew than on the plants themselves.

[6] http://www.co2science.org/articles/V7/N16/EDIT.php

> ***Nematode populations increased significantly in response to the 32% increase in the air's CO_2 concentration.***

Nematode populations increased significantly in response to the 32% increase in the air's CO_2 concentration. Of the various feeding groups studied, Yeates *et al.* report that the relative increase "was lowest in bacterial-feeders (27%), slightly higher in plant (root) feeders (32%), while those with delicate stylets (or narrow lumens; plant-associated, fungal-feeding) increased more (52% and 57%, respectively)." The greatest nematode increases, however, were recorded among omnivores (97%) and predators (105%). Most dramatic of all, root-feeding populations of the *Longidorus* nematode taxon rose by a whopping 330%. Also increasing in abundance were earthworms: *Aporrectodea caliginosa* by 25% and *Lumbricus rubellus* by 58%.

Enchytraeids, on the other hand, *decreased* in abundance, by approximately 30%. What are the ramifications of these observations? With respect to earthworms, Yeates *et al.* note that just as was found in the studies cited in the first part of this review, the introduction of lumbricids has been demonstrated to improve soil conditions in New Zealand pastures (Stockdill, 1982), which obviously helps pasture plants to grow better. Hence, the CO_2-induced increase in earthworm numbers observed in Yeates *et al.*'s study would be expected to do more of the same, while the reduced abundance of enchytraeids they documented in the CO_2-enriched pasture would supposedly lead to less carbon being released to the air from the soil, as per the known ability of enchytraeids to promote carbon loss from British peat lands under current temperatures.

Two years later, Bossuyt *et al.* (2005)[7] sized up the CO_2-earthworm situation as it was then understood by writing that "earthworms ingest large quantities of organic materials that are mixed and excreted as casts (Parmelee *et al.*, 1990; Martin and Marinissen, 1993; Jegou *et al.*, 1998) and improve stable macro-aggregation (Guggenberger *et al.*, 1996; Marinissen and Hillenaar, 1996; Scullion and Malik, 2000)," as had also been found to be the case by van Rhee (1977), De Vleesschauwer and Lal (1981) and McKenzie and Dexter (1987). In addition, they noted that "the retention of organic C in soil is becoming more important since the rise in atmospheric CO_2 and global warming are recent concerns," and that "earthworms are known to play a role in aggregate formation and soil organic matter (SOM) protection." However, they said "it is still unclear at what scale and how quickly earthworms manage to protect SOM." And, therefore, they conducted a pair of experiments designed to investigate this question.

In the first experiment, soil aggregate size distribution together with total C and ^{13}C were measured in three treatments -- control soil, soil + ^{13}C-labeled sorghum leaf residue, and soil + ^{13}C-labeled residue + earthworms -- after a period of 20 days incubation, where earthworms were added after the eighth day. In the second experiment, they determined the protected C and ^{13}C pools inside the newly-formed casts and macro- and micro-soil-aggregates. This work revealed that the proportion of large water-stable macro-aggregates was on average 3.6 times greater in the soil-residue samples that contained earthworms than in those that lacked earthworms, and that the macro-aggregates in the earthworm treatment contained approximately three times

[7] http://www.co2science.org/articles/V8/N13/B2.php

more sequestered carbon. As for what this all means, Bossuyt *et al*. state that the earthworms they studied were found to form a significant pool of protected C in micro-aggregates located within much larger macro-aggregates after 12 days of incubation, thereby demonstrating "the rapidity with which earthworms perform their vital function of sequestering carbon in soils when plant residues become available to them."

Also studying this important topic at two extensively managed grassland sites in Germany, were Don *et al*. (2008)[8], who worked with *anecic earthworms* that generally inhabit a single vertical burrow throughout their entire lives that can be as much as five meters in depth, analyzing soil carbon stocks and turnover via analyses of enzyme activity, stable isotopes, nuclear magnetic resonance spectroscopy, and the ^{14}C age of their burrow linings. This work revealed, as they describe it, that "the carbon distribution in soils is changed by anecic earthworms' activity with more carbon stored in the subsoil where earthworms slightly increase the carbon stocks." In this regard they also state that "the translocation of carbon from [the] organic layer to the subsoil will decrease the carbon vulnerability to mineralization," since "carbon in the organic layer and the surface soil is much more prone to disturbances with rapid carbon loss than subsoil carbon." And since they note that "earthworms are present in almost all ecosystems around the globe with particularly high abundances in grasslands, where they increase productivity (Partsch *et al*., 2006)," and where "100-800 burrows per square meter have been reported by Lavelle (1988)," it is evident that their presence and activity play important roles in helping Earth's soils store and preserve carbon ... and thereby mitigate the rate of rise of the atmosphere's CO_2 concentration.

In introducing another revealing study, Maraldo *et al.* (2010)[9] write that small oligochaete worms known as *enchytraeids* "are widely distributed from the Arctic to tropical areas, and typically inhabit the organic horizon in soils," where they "contribute to the decomposition

Maraldo *et al.* state that their experimentally-imposed warming had no significant impact on enchytraeid biomass production; but they found that their *drought* treatment *decreased* it by 40%. On the other hand, the extra 99 ppm of CO_2 *stimulated* enchytraeid biomass by 40%. And they remark that at certain times this latter phenomenon was "especially positive," as in the summer of 2007, when they say "the total enchytraeid biomass in the CO_2 plots was increased by 108% compared to ambient plots."

[8] http://www.co2science.org/articles/V11/N38/B3.php

[9] http://www.co2science.org/articles/V14/N3/B3.php

processes and nutrient mineralization," which activities have been shown to enhance nutrient availability and uptake by plants (Laakso and Setala, 1999; Cragg and Bardgett, 2001). And enchytraeids provide these benefits *directly*, as Maraldo *et al*. describe it, "by consuming large amounts of organic matter," and *indirectly* "by their feeding activity and modifications of soil structure." In addition, they note that "the presence of enchytraeids is especially important in nutrient poor ecosystems," such as "temperate heathland and northern coniferous forests, where their biomass dominates the soil faunal community," citing the work of Cragg (1961) and Swift *et al.* (1998).

Working on a hilly nutrient-poor sandy soil with a dry heath/grassland cover at Brandbjerg, Denmark, the seven scientists conducted an experiment that was begun in October 2005 and extended through 2007. There they studied the individual and combined effects of (1) *soil warming:* a mean daily temperature increase of 0.3° in winter and 0.7° in summer at a depth of 5 cm, provided by a scaffolding that carried a curtain -- which reflected the outgoing infrared radiation from the soil/plant surface back toward the ground -- that was automatically pulled over the vegetation at sunset and retracted at sunrise, (2) *drought:* peak soil water content reductions of 11% and 13% compared to control plots in 2006 and 2007, provided by waterproof curtains that were automatically pulled over the vegetation during rain events, and (3) *atmospheric CO_2 enrichment:* a CO_2 concentration increase from 382 to 481 ppm, provided by a free-air CO_2 enrichment or FACE system.

In reporting the findings they thereby obtained, Maraldo *et al.* state that their experimentally-imposed warming had no significant impact on enchytraeid biomass production; but they found that their *drought* treatment *decreased* it by 40%. On the other hand, the extra 99 ppm of CO_2 *stimulated* enchytraeid biomass by 40%. And they remark that at certain times this latter phenomenon was "especially positive," as in the summer of 2007, when they say "the total enchytraeid biomass in the CO_2 plots was increased by 108% compared to ambient plots." As for interactions among the three factors, they report there were none, so that "the positive effect of increased CO_2 [+40%] and the negative effect of drought [-40%] were cancelled out when applied in combination."

In another enlightening study, Sanchez-de-Leon *et al*. (2014)[10] write that "the physical protection of carbon in soil aggregates is a key mechanism affecting soil carbon dynamics (e.g. Tisdall and Oades, 1982; Six *et al.*, 2004; Blanco-Canqui and Lal, 2004; Jastrow *et al.*, 2007)," while further noting in this regard that "stabilization of soil organic carbon (SOC) in aggregates decreases its accessibility to microbes and soil fauna," which thereby protects SOC from rapid mineralization and increases its in-soil residence time (Sollins *et al.*, 1996; Marinissen and Hillenaar, 1997; Jastrow *et al.*, 2007).

More specifically, as they describe it, the five U.S. researchers "conducted a 26-day laboratory incubation experiment using plant and soil materials with differential dual isotopic compositions obtained from different CO_2 and ^{15}N-labeling treatments at the Oak Ridge National Laboratory (ORNL) FACE [Free-Air CO_2 Enrichment] site," where they used crushed and sieved unlabeled soil to create four treatments: (I) soil only; (II) soil and plant material; (III) soil, plant material and the

[10] http://www.co2science.org/articles/V17/N14/B3.php

> *"Earthworms at the ORNL-FACE site directly contribute to the formation of soil aggregates and could be an important factor contributing to the soil stabilization of increased recent carbon inputs resulting from atmospheric CO_2 enrichment."*

native, endogeic earthworm *Diplocardia* sp.; and (IV) soil, plant material, and the European, epiendogeic earthworm *Lumbricus rubellus*," where the added plant materials consisted of both sweetgum (*L. styraciflua*) leaf and root litter. And what did they thereby learn?

Sanchez-de-Leon *et al.* report that (1) "overall, earthworms increased the mass of newly formed soil macro-aggregates," that (2) "most of the carbon within macro-aggregates was soil-derived," and that (3) "leaf- and root-derived carbon was found only in the treatment with *L. rubellus.*" And so it was that they learned that "the source of carbon within macro-aggregates paralleled earthworm feeding ecologies, with endogeic earthworms feeding mostly on soil organic matter and epi-endogeic earthworms feeding on both plant residues and soil organic matter," leading them to conclude that "earthworms at the ORNL-FACE site directly contribute to the formation of soil aggregates and could be an important factor contributing to the soil stabilization of increased recent carbon inputs resulting from atmospheric CO_2 enrichment," one of the significant consequences of which -- in the eyes of the world's climate alarmists -- is to slightly reduce the rate at which the air's CO_2 content continues to rise.

In summary, it would appear that the lowly earthworm and still lowlier soil nematodes respond to increases in the air's CO_2 content via a number of plant-mediated phenomena in ways that further enhance the positive effects of atmospheric CO_2 enrichment on plant growth and development, while at the same time helping to sequester more carbon more securely in the soil and thereby reducing the potential for *postulated* CO_2-induced global warming.

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