Can foraging for earthworms significantly reduce global famine in a catastrophe?

Henry Miller [a], *James Mulhall* [a*], *Lou Pfau* [a], *Rachel Palm* [a,b], *David C. Denkenberger* [a,c]

Affiliations:

[a] *Alliance to Feed the Earth in Disasters (ALLFED), Lafayette, CO, 80026 USA*

[b] *University of the National Education Commission, Krakow, Poland*

[c] *University of Canterbury Department of Mechanical Engineering, Christchurch, New Zealand*

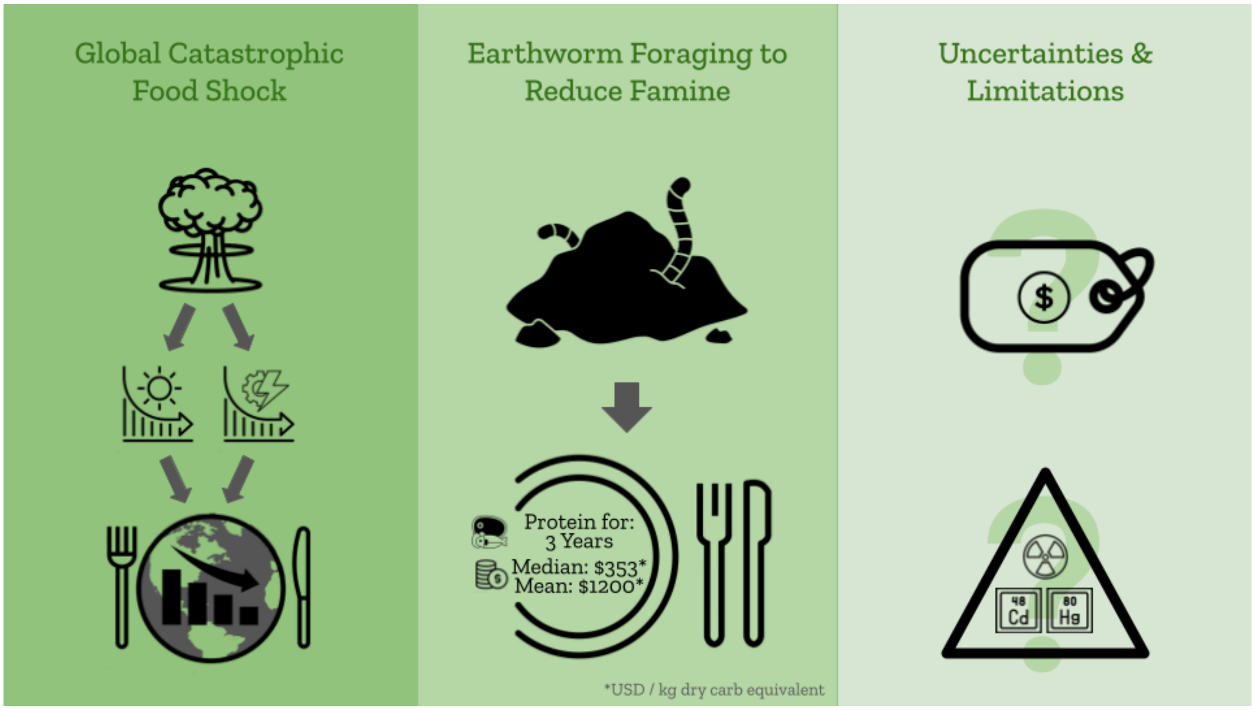
**Corresponding author: james.m@allfed.info.*

Abstract

Earthworms are a resilient group of species that thrive in a variety of habitats through feeding on decaying organic matter, and are therefore predicted to survive an abrupt sunlight reduction scenario, such as a nuclear winter. In this study, the feasibility and cost-effectiveness of foraging earthworms to reduce global famine following a reduction in sunlight with or without global catastrophic loss of infrastructure was considered. Methods for extracting worms were analysed, along with scalability, climate-related barriers to foraging, and pre-consumption processing requirements. Estimations of the global earthworm resource suggest it could provide three years of the protein needs of the current world population, at a median cost of 353 USD·kg^{-1} dry carbohydrate equivalent or a mean cost of 1200 (90% confidence interval: 32–8500) USD·kg^{-1} dry carbohydrate equivalent. This is more expensive than other resilient food options and, moreover, earthworms may bioaccumulate heavy metals and other contaminants, presenting a health risk. While costs appear high, there are a number of uncertainties that remain to be addressed. In particular, earthworm biomass distribution may be higher in specific locations. Real-world news reports of earthworm foraging in China and Vietnam detail high yields, suggesting a targeted approach to foraging in the most abundant regions could provide a more feasible application of earthworms as a resilient food source.

Keywords: resilient food, earthworms, foraging, global catastrophic risk, existential risk, nuclear winter

Graphical Abstract



1 Introduction

Earthworms feed on decaying plant matter in and on the soil; it is therefore reasonable to think they will continue to survive in the immediate aftermath of an abrupt sunlight reduction scenario (ASRS). The co-occurence of an ASRS and global catastrophic infrastructure loss (GCIL) would result in extreme levels of food insecurity without prior preparation. This scenario is described fully by Denkenberger et al. [1]. In brief, a large-scale nuclear exchange could trigger a nuclear winter, blocking out sunlight, and multiple high-altitude electromagnetic pulses, destroying electricity grids over large areas and collapsing industry. Another combination scenario is the blocking of the sun in the future if our energy system is very dependent on the sun (relying on technologies such as solar and wind power). Alternative paths to this scenario exist, such as asteroid impact, comet impact, or supervolcanic eruption for blocking out sunlight; and extreme solar storms, coordinated cyber attack, or extreme pandemic causing people to be unwilling or unable to come to work in critical industries for industry collapse. These latter scenarios, those requiring two independent events, appear less likely than nuclear war [1]. However, a possible mechanism for the dependence of events could be that in times of famine, pandemics are more likely [2]. This is due to people's impaired immune system, but could also be caused by people eating more wild animals, exposing them to zoonotic pathogens [3].

Preventing global food insecurity requires planning resilient food solutions; defined by Pham et al. [4] as "foods, food production methods or interventions that would allow for significant food availability in the face of a global catastrophic food shock. These solutions should be well-suited for contributing to an adequate food supply for the greatest number of people even in the worst scenarios." Numerous promising resilient food solutions have been proposed, such as ramping up seaweed production [5], crop relocation, extracting edible calories from killed leaves, growing mushrooms on dead trees, fishing [1], repurposing paper mills to produce lignocellulosic sugar [6], crop relocation [7], and building methane single cell protein factories [8]. Resilient foods also increase the chance that trade is maintained, which would dramatically increase the number of people fed [7]. However, many of these are reliant on industrial processes and have significant ramp up times. While wood gasification could possibly provide an energy source for tractors, it too is associated with a significant ramp-up time. One advantage of earthworm foraging would be its immediate accessibility, providing a potential short-term food source while alternatives are developed.

Across the globe, earthworms have provided a source of nutrition for people in many societies [9–12] as well as a safe feed ingredient for livestock [13–15]. There are also reported instances of people earning a living from collecting and selling wild earthworms [16]. Earthworms can be collected using basic equipment and technology. This raises the question of whether recovering societies could source a significant fraction of their nutritional needs through foraging wild earthworms following an ASRS with or without GCIL. To answer this, it is necessary to address the following points:

1. How many earthworms are there in accessible land on Earth?
2. What is the potential nutritional value of the earthworm population?
3. What methods of collecting earthworms are available and how suitable might they be for the above mentioned scenario?
4. What would be the time and labour costs for producing nutrition from earthworms and how do they compare to other resilient foods?
5. How confident can we be in these calculations and what limitations contribute to our uncertainty?

Academic sources were prioritised when writing this article and it has been made clear where uncertainties were introduced by lower quality sources. A mathematical model estimating the availability of earthworms and costs of foraging for them was produced using Guesstimate, a probabilistic modelling tool. This software performs Monte Carlo analysis to propagate uncertainty of parameters in calculations and, due to the random generation of samples, the values in the model may differ slightly from those shown below. However, they are still within an order of magnitude and therefore do not change the general conclusions of this article. The earthworm model in Guesstimate is publicly available online [17].

2 Materials and Methods

2.1 Estimating the global biomass and nutritional potential of earthworms

A recent study [18] suggests the abundance of earthworms varies significantly across different environments, with the majority of sites having a wet matter abundance between 1 and 150 $g{\cdot}m^{-2}$. The predicted mean for the territories earthworms inhabit was 51 $g{\cdot}m^{-2}$.

The total amount of land available for foraging earthworms can be estimated using data on land usage from the Food and Agriculture Organization of the United Nations [19] and the analysis available from Our World in Data [20]. Excluding uninhabitable or barren land; land covered by ice sheets, fresh water, sand or bare rock; and urban land, where infrastructure could prevent access to earthworms; there are 10.3 billion hectares of accessible land. This is composed of arable land, pasture, shrub covered land, and forests [20]. The feasibility of accessing land in each subtype and foraging earthworms will vary, as will the abundance of earthworms, but for the purposes of this article it is assumed that all the land area is available for foraging with the mean abundance of earthworms stated previously. The product of these two numbers gives a total earthworm biomass of 5.3 billion tonnes.

Estimated total earthworm biomass can be combined with dry matter content and nutritional data to quantify the calories, protein, and fat available from worms. The dry matter content of earthworms varies with the environmental conditions [21] and species [22], with values of 15.2% [22], 15.7% [23], and 20% [22] present in the literature; each one represents a species of a different ecological category [18,cf. 24,25]: *Lumbricus terrestris* (anecic) [25,cf. 24], *Eisenia fetida* (epigeic) [26,cf. 25], and *Allolobophora chlorotica* (endogeic) [25,cf. 24] respectively. Since the categories signify earthworm living and feeding behaviour and thus aboveground or belowground presence [25], taking the distinction into account for evaluating and implementing certain foraging endeavours may be important. Nevertheless, such incorporation remains challenging: many species belong to multiple categories [24], while proposed models for category abundances feature significant uncertainties [27] or limitations [28], with biotic interactions between categories [27,29] and the type of habitat [18,27,28], among others, contributing to the earthworm diversity. As a result, the estimate remains agnostic in terms of detailed distribution of earthworm dry matter content and nutritional value per each category, generalising the findings through the use of arithmetic mean. Similarly, habitat is generalised to earthworm-habitable land, as per above. Considering the three dry matter content values, a mean of 17% suggests there are 900 million tonnes of earthworm dry matter available globally. The nutritional value of earthworms is described for earthworm meal with dry matter crude protein content in the range of 53.8% to 72.9% [11,12,23,30] depending on the species and the method of preparing earthworms for consumption. Taking the mean from several nutritional values for whole earthworm dry matter of 60.7% estimates the global earthworm nutritional protein resource is 540 million tonnes. The energy content of earthworms is less widely reported, but a mean estimate of 4.068 $\text{kcal}\cdot\text{g}^{-1}$ of dry matter can be derived from Sun et al.'s value for partially dried *Eisenia fetida* worm meal [23] and Kavle et al.'s [11] value for *Eisenia andrei*. The total nutritional energy resource is 3.65×10^{15} kcal equivalent to 910 million tonnes of dry carbohydrate. Epigeic earthworms have mean dry matter fat content of 13.7% as derived from the literature [11,23], suggesting the total dietary fat resource of the earthworm population is 122 million tonnes. Based on World Health Organisation requirements for daily fat intake to comprise at least 15% of daily caloric intake [31,32], earthworms could represent a significant nutritional resource.

When compared to global nutritional requirements, these estimates indicate that the total wild earthworm population could provide a significant supply of energy and macronutrients for humans (Table 1). The most abundant macronutrient, relative to demand, is protein, but the fat supplied could be of particular value following an ASRS with GCIL [33]. Each person would require 500 g of fresh earthworms to meet their daily protein requirement harvested from an average area of 10 m^2. It is necessary to establish whether this resource can be accessed by people and at what cost.

Table 1. Estimations of the nutritional potential of the global earthworm population in relation to the nutritional demand of the current human population.

Global Population	8.07 billion [34,35]
Daily Protein Requirement per person	51 g [36,37]
Daily Energy Requirement per person	2100 kcal [38]
Daily Fat Requirement per person	315 kcal

	Daily Global Requirement		Potential Earthworm Resource		Potential Days of Nutrient from Earthworms
Protein	4.15×10^{11}	g	5.44×10^{14}	g	1310
Energy	1.69×10^{13}	kcal	3.65×10^{15}	kcal	220
Fat	2.54×10^{12}	kcal	1.10×10^{15}	kcal	440

2.2 Methods for extracting living earthworms from the soil and efficiency thereof

Ecologists have collected earthworms for over a hundred years, including Charles Darwin [39], the renowned proponent of the theory of evolution through natural selection [40]. A literature search was conducted to identify different collection methods, considering techniques used in scientific studies, by commercial foragers, and by recreational foragers such as fisherfolk. Numerous foraging methods have been reviewed comprehensively by Rhea-Fournier and González [41], but a select few are discussed below after consideration of their suitability for foraging edible earthworms following an ASRS with or without GCIL. In general terms, extraction techniques rely on disruptive excavation of soil with physical separation of earthworms from the substrate, or induction of surfacing behaviour in earthworms so they can be collected from the ground. Each method was investigated until it was eliminated as a viable option or until a full Guesstimate cost model was generated (i.e., for electroshocking [17]). The predicted time and costs incurred for different methods have been expressed in terms of extracting the global earthworm resource estimated above but, more practically, as a cost to provide the nutritional requirements for each person. In general, earthworm foraging methods were immediately deemed cost-ineffective if they were an order of magnitude more expensive than other resilient food options. To establish a method as cost-effective, context-specific analysis would be necessary. Three quantitative factors must be known for an estimate of the usefulness of each method:

1. The percentage of the earthworm population in the soil that can be harvested (extraction percentage).

2. The area of land foraged per application of a method (effective area).
3. The time taken per application of a method (cycle time).

Focusing on land areas with higher than average earthworm biomass would increase the efficiency of foraging. Therefore, where selective collection methods may be applied, the availability of earthworm biomass is adjusted upwards.

3 Results and Discussion

3.1 Feasibility and cost-effectiveness of extracting earthworms from the ground

3.1.1 Mechanical sorting of soil

The simplest methods of extracting earthworms from the soil are to locate and collect worms by manually or mechanically sieving excavated earth. Digging followed by hand sorting or washing-sieving [42] is the reference standard method for measuring the total population size of earthworms, with up to 100% of macroscopic earthworms collected. However, it is incredibly labour intensive [41], so mechanical tools have been developed to accelerate the process [43]. The depth of soil excavated varies from 0.2 to 0.5 m. Even if 100% of earthworms could be collected by removing the top 0.35 m of soil from any given area, the total volume of excavated soil to harvest the entire earthworm population would still be excessively high at 3.61×10^{13} m^3. To meet the daily protein requirements of a single person would require sorting an average of 3.41 m^3 (5120 kg) of soil. Lin et al. recently published results on a novel specialised mechanical worm separator capable of retrieving 83.8% of worms from 21.2 kg of substrate per minute [43]. At this rate, it would require 5 hours to collect a person's daily protein intake of earthworms without consideration of the time taken to excavate and transport the soil to the sorting machine. Field trials of excavation and soil sorting are necessary to improve the predictions of the precise costs of this method; however, the preliminary modelling suggests sorting of soil would not be a practical method of harvesting wild earthworms to feed a large population. Scaling up the method would require production of a large number, at least one per five people, of mechanical earth sorters and the removal of enormous quantities of soil. In a scenario with GCIL, it would not be feasible.

3.1.2 Worm charming or grunting

Worm charming, or grunting, is another physical technique for collecting earthworms. Rubbing a metal 'rooping' iron, such as an automobile leaf spring, across the top of the stake creates vibrations inducing worms to surface within a 12 m radius of the stake [16]. There are numerous reports of worm collecting competitions. Generally, participants agitate the ground and generate vibrations with music, garden tools, or probes that cause earthworms to come to the surface [44]. It has been suggested that earthworms surface to avoid moles, with the vibrations mimicking that of the predator [16], although this has only been reported as a causal relationship for one species of earthworm.

The literature on worm grunting is limited, but a few authors have quantified the number of worms surfaced from such techniques. Catania [16] describes how two professional worm grunters, Gary and Audrey Revell, earn a living in Florida, USA by selling earthworms for fishing bait. The distribution of surfaced worms charmed by the Revells is analysed, but time and extraction efficiency are not listed. Mitra et al. [44] conducted a similar experiment in Apalachicola National Forest, Florida. They did record time, but not extraction efficiency. While these studies show promising numbers of surfaced worms, the results cannot be extrapolated for global analysis without extraction efficiency data. At this time, there is insufficient evidence to support grunting as a viable option for scalable, cost-effective foraging. However, the equipment required is inexpensive, could be scavenged in large quantities from readily available sources, and requires no electricity or mechanised power. This technique may also allow large areas of land to be foraged quickly. If further research showed that untrained individuals were able to reach high levels of extraction efficiency, grunting could be revisited as a foraging technique.

3.1.3 Chemical earthworm expellents

There are a wide range of chemicals, known as vermifuges, that cause earthworms to surface when applied as a solution onto soil [41]. These include household detergent, formaldehyde, potassium permanganate, mustard solution, onion solution, and allyl isothiocyanate (AITC) [41,45]. Household detergents are reported to yield an order of magnitude fewer earthworms compared with the other solutions [45]. As a known carcinogen and hazardous solution [46], formaldehyde is not suitable for treating food. Potassium permanganate is recognised as safe for the treatment of food. However, it is reported that worms collected from soil treated with potassium permanganate solution disintegrate unless fixed in formalin [47], again limiting its applications for foraging. Mustard and onion solutions are both non-toxic, but using them requires the diversion of agricultural products away from direct food consumption. While it is reported that the application of onion solution to soil yields more earthworms than application of formalin or AITC [48], the mass of onion required is unlikely to be sustainable. Steffan et al. reported optimal extraction efficiency using 700 g of fresh onions in 4 L of aqueous solution to treat an area of 0.196 m^2, yielding 16 $g \cdot m^{-2}$ of earthworms [49] equating to the cost of 223 g of onion per gram of fresh earthworms. Even if the efficiency of this process were increased tenfold, it is unlikely to be appropriate following an ASRS with GCIL. AITC is a synthetic version of the active compound in mustard solution, with production dependent on industrial chemical processing, making it unsuitable for the scenario described above.

The effectiveness of vermifuges is recognised to vary depending on the species of earthworms present in the soil as well as the permeability of the soil to liquid. For instance, chemical expellents may be unsuitable for clay rich tropical soils, as low soil permeability prevents solutions from entering earthworm burrows [41]. Therefore, predictions of their usefulness for the global harvesting of earthworms are uncertain. Another practical consideration against the use of vermifuges is the large volume of solutions that would be required to treat soil. Taking a rate for vermifuge application of 20 $L{\cdot}m^{-2}$, a conservative lower estimate based on a range of chemical extraction studies [48–52], and a 50% extraction efficiency suggests 400 L of solution would be required to harvest the daily nutritional protein for each person, a potentially prohibitive mass of fluid to transport and apply repeatedly.

Chemical expellents do not appear to be a promising solution for the large-scale foraging of wild earthworms.

3.1.4 Electroshocking

In the academic literature, there is a long history of a technique known as electroshocking: applying an electrical current to soil for the purpose of collecting earthworms. Academic overviews are provided by Rhea-Fourier and González [41] and Singh et al. [45]. The basic technique requires insertion of electrodes approximately 45 cm into the soil followed by connection to a power supply so that current flows through the surrounding soil. The current is applied for a set period of time, during which earthworms escape to the surface in a radius around the electrodes. Here, they can be collected alive from the surface once the electrode is switched off or while wearing electrically insulating gloves. A unipolar approach is simplest, with current applied through a single electrode directly to the soil [53]. The use of both positive and negative electrodes to create a defined electric field through the soil is also possible. An electrical octet, arrangement of four pairs of electrodes applying voltage across the soil in multiple directions, is reported to give the highest earthworm extraction efficiency [41,54–56]. Alternating current (AC) is preferred over direct current (DC), necessitating either a generator for the electricity power supply or a DC to AC inverter if batteries are used [55].

A probable benefit of electroshocking as a scalable foraging technique is the very low requirement for operator skill, though safe product design is crucial to minimise risks of electric shocks [57]. It can also be performed without physical or chemical disruption of the ecosystem [41], and so may be compatible with other land usage such as growing crops.

As far as the authors are aware, no studies have been conducted with the specific purpose of maximising the biomass of earthworms harvested using electroshocking. Therefore, estimates of the potential yield, labour, and energy costs of this technique have been produced by extrapolating from a number of reports (Table 2). Using the parameter ranges stated below and estimates of earthworm abundance as described previously, we created a mathematical model for the costs of foraging earthworms using electroshocking. The model is publicly available through Guesstimate [17]. This tool applies random variation and Monte-Carlo simulations to parameters in order to generate a predicted range of outcomes. The estimated range of values for earthworm biomass density in this model is based on Phillips et al. [18]. The upper limit of 150 $g \cdot m^{-2}$ was derived from the authors' own description of the data, "*biomass typically ranged (97.3% of pixels) between 1 g and 150 g per* m^2", with the median value of 6.16 $g \cdot m^{-2}$ used as the lower limit. It was assumed that pilot sampling of land using digging and hand sorting/wash sieving could increase the productivity of foraging through selection of the 50% of sites with the highest earthworm biomass density. Examination of the raw data set indicated a log-normal distribution within this range gave the closest fit [58].

Table 2. Input parameter ranges used in a model describing sourcing food through the foraging of earthworms by electroshocking.

Parameter	**90th Percentile Range**	**Reasoning**
Extraction percentage	10–88%	Satchell did not give an extraction percentage for the total earthworm population, but the data show electroshocking to yield 10% of the number of worms extracted using potassium permanganate [53]. A patent filed by Thiellemann for an electrode octet earthworm extractor reports 87.7% of earthworms were extracted with the equipment [56].
Effective area	0.22–2.6 m^2	Weyers et al. [55] built an electroshocking device that covered an area of at least 0.22 m^2. Satchell [53] refers to earthworms surfacing up to 3 feet from the electrode. A circle of this radius has an area of 2.6 m^2.
Cycle time	20–40 minutes	Thiellemann [56] reports a cycle taking approximately 20 minutes. Satchell gives figures for earthworms collected after 40 minutes [53].
Electrical supply voltage	30–480 V	Thiellemann states a minimum voltage required of 30 V [56]. Weyers et al. applied an effective maximum of 480 V [55].
Electrical supply current	0.2–4 A	Rhea Fourier and González state 0.2 A as the lower effective current for extraction [41]. Satchell maintained an upper limit current for 4 A [53].

Number of electrodes managed in series	3–10	Estimate based on unpublished reports of earthworm electroshocking in the media [59].
Hourly wage for labour	1.8–13.8 USD per hour	The OECD.Stat data show the range of hourly minimum wages in member nations was 1.8 to 13.8 USD per hour in 2022 [60] when expressed with purchasing power parity.
Length of a working day	6–12 hours	Daily rest requirements of 12 hours were assumed, as informed by International Labour Organization data [61,62].

This model indicates predicted mean labour costs (90% CI) of 0.31 (0.0081–2.1) $\mathrm{USD{\cdot}kcal^{-1}}$ of nutritional energy, 2.3 (0.053–14.0) $\mathrm{USD{\cdot}g^{-1}}$ of protein, and 1.3 (0.029–8.6) $\mathrm{USD{\cdot}kcal^{-1}}$ of fat. Taking a dry carbohydrate equivalent labour cost of 1200 (32–8500) $\mathrm{USD{\cdot}kg^{-1}}$, the cost of earthworms is 1–3 orders of magnitude higher than current resilient foods listed by Denkenberger et al. [63]. It is estimated to take a single worker an average of 17 hours to forage enough protein to meet the daily requirements of a single person, ruling this method out as a feasible supply of dietary protein across the globe. However, the median dry carbohydrate equivalent labour cost is 353 $\mathrm{USD{\cdot}kg^{-1}}$, with 6 hours of foraging required for one person's daily protein requirements. While still relatively expensive compared with most resilient foods, this suggests collecting earthworms may be more viable if targeted to a small subset of locations.

Brief consideration can be paid to the electrical energy needs for scalable electroshocking of earthworms. This model predicts a mean use of 2.3 MJ of electricity per g of dietary protein, equating to approximately 340% of global electricity production in 2022, to meet global demand for protein from earthworm foraging. The median prediction is 0.4 MJ of electricity per g of dietary protein, or approximately 59% of global electricity production in 2022. For comparison, production of methane single cell protein, a resilient food, requires 0.11–0.15 MJ of energy per g of dietary protein [8]. However, the majority of this energy is from natural gas, with a smaller fraction from electricity. As electricity supplies may have to be prioritised for the most productive activities following an ASRS with GCIL, and there may be additional difficulties bringing large amounts of electricity into the field, this method does not appear viable for combination catastrophes. However, given the median electricity requirement is comparable to that of methane single cell protein, electricity does not appear to be the bottleneck for targeted electroshock foraging in an ASRS without GCIL.

3.2 Climate related barriers to foraging wild earthworms

Wild earthworms represent part of a large natural ecosystem that is liable to change substantially following an ASRS with likely ramifications on the feasibility of foraging for them as food. The most pertinent are changes in soil temperature and precipitation levels.

3.2.1 Reduced temperature may prevent earthworm foraging

Following an ASRS, global surface temperatures are predicted to fall substantially. The degree of global cooling caused by nuclear conflict is hotly debated, with predictions of up to an 8 ℃ [64] reduction. This uncertainty precludes precise predictions of how earthworm foraging will be affected, yet there are some general considerations.

As 'cold-blooded' species, the biological activity of individual earthworms is affected by the environmental temperature [65]. Singh et al. provides a thorough review of the effects climate change may have on earthworm populations [66]. Reynierse [65] reports that reducing the environmental temperature for one species of earthworms from 24 ℃ to 10 ℃ did not consistently reduce their locomotor activity after the environmental temperature stabilised. In contrast, many individual studies have observed a reduction in the reproductive rate and physical activity of earthworms as environmental temperature falls [67–69] (although adults of earthworm species achieving maximum mean weight during winter have also been reported [26]). Earthworms exhibit behavioural adaptations to cold temperatures in temperate climates mainly through burrowing more deeply into the soil [70] to avoid freezing. Even though there are reports on freeze-tolerant earthworm species with individuals able to survive temperatures of -20 ℃ [71] or lower [72], the majority of species do not employ overwintering strategies for remaining in upper soil layers. While some earthworm species' cocoons containing eggs can survive freezing temperatures, adults might not [70]. In general, significant cooling of the soil is expected to reduce the accessible earthworm population in the topsoil. These behavioural and activity effects may also reduce the efficiency of foraging.

Overlaying 150 Tg nuclear winter temperature predictions [64] onto earthworm biomass density distributions [58] suggests the long-term availability of worms may be considerably lower in a severe ASRS (Figure 1). Many of the areas with the highest earthworm biomass density, including Canada and Central and East Asia, would suffer freezing conditions which could substantially reduce the accessible wild earthworm resource. The ground could become too hard to break through, preventing humans from inserting electroshock probes into the ground or digging for worms. Additionally, earthworms may not be able to penetrate the topsoil to surface. Moreover, the previously described risks of reduced earthworm activity would extend to this area and beyond, including land that reaches cold but not freezing temperatures (Figure S1). These effects add a time-sensitive aspect to earthworm foraging, though collecting worms in the early stages of a catastrophe before temperatures drop significantly may minimise the difficulties of freezing zones.

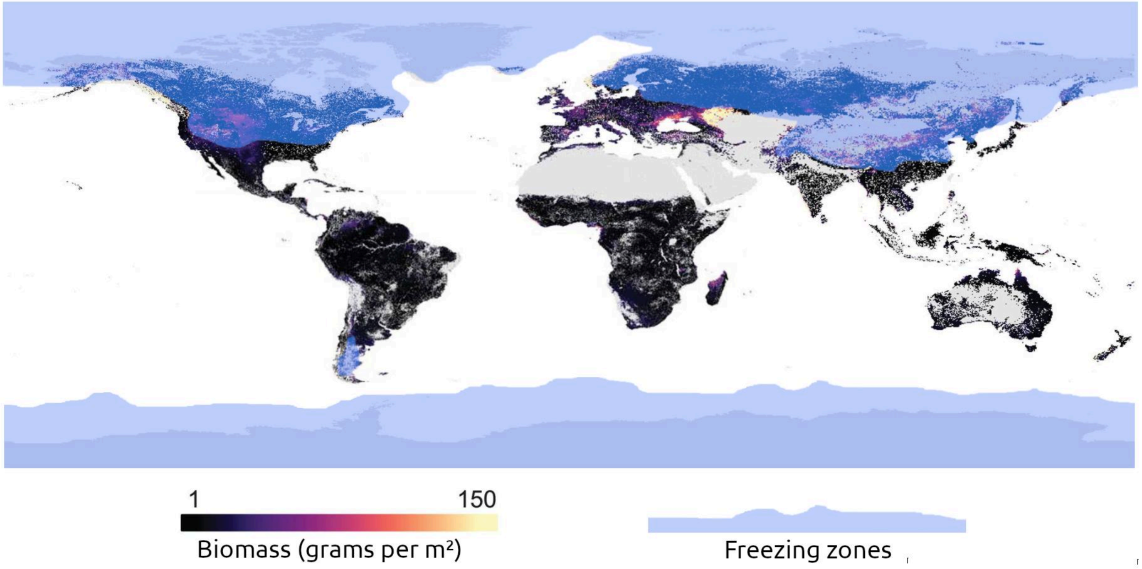


Figure 1: Overlap of global earthworm distribution and nuclear winter freezing zones. Earthworm biomass is displayed, overlaid with frozen land areas (temperature < 0℃), shaded in blue. Frozen land area is based on predicted average surface temperature for June, July, and August following a 150 Tg nuclear conflict in the Northern Hemisphere in the month of May. Adapted from Phillips, H.R.P.; Guerra, C.A.; Bartz, M.L.C.; Briones, M.J.I.; Brown, G.; Crowther, T.W.; Ferlian, O.; Gongalsky, K.B.; van den Hoogen, J.; Krebs, J.; et al. Global Distribution of Earthworm Diversity. Science 2019, 366, 480–485, doi:10.1126/science.aax4851. Adapted with permission from AAAS. Freezing zones based on Coupe, J.; Bardeen, C.G.; Robock, A.; Toon, O.B. Nuclear Winter Responses to Nuclear War Between the United States and Russia in the Whole Atmosphere Community Climate Model Version 4 and the Goddard Institute for Space Studies Model. E. J. Geophys. Res. Atmospheres 2019, 124, 8522–8543.

3.2.2 Reduced precipitation may affect earthworm abundance

Climate modelling of an ASRS predicts a reduction in precipitation [64] alongside lower temperatures. Earthworm activity and reproduction is affected by the moisture level in soil, a factor that will be influenced by changes in precipitation and temperature [66]. This factor warrants consideration in future work modelling the availability of earthworms as a food source in this scenario, though it is less important for the immediate harvest available.

3.3 Processing earthworms for consumption

Once harvested, it is recommended to remove the soil content from the gastrointestinal tract of earthworms before consumption. Soaking earthworms in water for 3 hours [14] or manually expelling the gut content [12] are among suggested solutions. Several methods of earthworm slaughter are described, including immersion in acetone [14], lyophilisation (freeze-drying), osmotic shocking (salting or brining) and blanching [15] in 60 ℃ to boiling water, and eating them fresh [12,73]. Blanching in water is technologically the simplest processing method, maintains the highest nutritional value of earthworms, and reduces taint from coelomic fluid lysenin protein [15]. Through cold water soaking followed by blanching, earthworms can be prepared for eating without any significant technological, labour-intensive, or costly processes. For microbiological safety of human consumers, creation of sterilised defatted earthworm meal is recommended. This is obtained by several steps including: washing the earthworms in tap water repeatedly, leaving them in the liquid until gut content excretion (in between the washing iterations), killing them by storing at -28 ℃ in sealed plastic bags, freeze-drying, grinding, delipidating, and eventually sterilising them in a steam autoclave at 121 ℃ for 20 minutes; although sterilisation is identified as the critical control point, the specific last step may reduce the nutritional value of the end-product [74].

3.4 Significant limitations and uncertainties

In reviewing the material available for this study, it was apparent that there are several areas of uncertainty which could affect predictions of how suitable earthworm foraging would be as a food source in an ASRS with GCIL. Specific examples are highlighted below with reference to whether they suggest greater or lesser feasibility of humans using wild earthworms as a food source.

3.4.1 The dataset for global earthworm abundance is limited and may underestimate the resource

The estimates of global earthworm abundance in this article are based on a published study by Phillips et al. [18] and the corrected data set associated with it [75]. However, the model described in the paper has been criticised for excluding earthworm survey data collected prior to the year 2000 [76,77]. Moreover, it has also been criticised for extrapolating from geographical point data which may have led to underestimation of earthworm abundance [77]. Earthworm populations in the tropics are underrepresented in the dataset, and its authors admit surprise that their model predicts such a low biomass density in tropical areas. An illustration of the academic uncertainty is a report by Blakemore, which concluded that the global earthworm dry biomass amounts to 4.5 gigatonnes [78], fivefold higher than the estimate calculated above. Blakemore's figure is based on a series of earthworm surveys predating 1985 [79] and assumes the much larger area of earthworm habitable land of 2.4 × 10^{14} m^2, which may explain the discrepancy in the findings. It is possible that future work will recognise a much higher biomass of earthworms in the tropics and possibly a higher average biomass globally, both of which could increase the size and accessibility of wild earthworms as a food source.

This article has not covered the potential for earthworms to be foraged specifically in areas with very high biomass density, but they may be a cost-effective food source in these areas. More detailed analysis accounting for the size and biomass density in local regions across the globe would be valuable for this study. An additional area of uncertainty is the exact nutritional value of the global earthworm population due to the heterogeneity of species, differences in reported methods for measuring the nutritional value of earthworm samples, and inconsistencies in the reported metrics of nutritional content. An exhaustive literature review was outside the scope of this article, but, in the authors' opinion, differences in the nutritional content would not be large enough to alter the conclusions of this study.

3.4.2 Worm grunting, or charming, is promising but reliable data are lacking

The academic literature on quantifying worm grunting and charming is scarce, but these techniques have quite a significant presence in public media. Unreviewed reports indicate that potential earthworm yields may be very high with relatively low labour and equipment costs. The Guinness World Record [80] for worm charming is 567 earthworms collected in 30 minutes from 3 m^2 of land, and worm grunters reportedly can collect thousands of worms in a few hours [44]. With scientific studies validating these findings and providing information on the extraction percentage for the techniques, it would be possible to predict, and possibly recommend, the use of such promising methods for foraging for earthworms in a disaster scenario.

3.4.3 Reports of high yields from electroshocking are unconfirmed by scientific literature

Recent media attention suggests earthworm electroshocking equipment is cheap and readily available in China and Vietnam. Furthermore, many people claim to collect over 100 kg of earthworms per day for slaughter and sale [59,81,82]. This yield is orders of magnitude greater than that predicted by models based on the scientific literature. Reliable descriptions of the equipment and context that permits such large quantities of worm biomass to be foraged could improve predictions of the scalability of this method. If such a technique were to be recommended, it would be necessary to establish quantitative estimates of the availability of resources such as AC generators.

3.4.4 Foraged earthworms may be harmful for humans

Earthworms cannot be recommended as a resilient food, intended to supply a significant proportion of a person's macronutrient requirements, unless proven to be safe when consumed as a substantial fraction of the human diet. Annual consumption rates of up to 2 kg of earthworms per person per year are reported in the literature [12]. However, if foraged earthworms were adopted as a scalable resilient food source, annual consumption per capita could be much higher, increasing the risk of consumers being exposed to any foodborne hazards. Food hazards are commonly categorised as chemical (e.g. heavy metals or pesticides), biological (e.g. microbial pathogens), or physical (e.g. extraneous material) [83]. The risk of food derived from foraged earthworms presenting a risk to human health due to these hazard groups are addressed in turn below.

Earthworms bioaccumulate toxic substances from the soil substrate in their body tissues [84,85]. This process is pertinent to food safety because human industrial activities have released a number of toxic chemicals into the soil which pose a risk to human health should they enter the food chain [86]. Removing chemical hazards, such as heavy metals, from food requires expensive and technologically advanced techniques [87] preventing a simple mitigation strategy in an ASRS with GCIL. The level of chemical residues in earthworms is dependent on the level of chemicals in the soil [84,85] or substrate, suggesting the risk of this hazard to human health will vary across different environments. It has been demonstrated that wild earthworms can contain measurable quantities of heavy metals [84], including several which have clear maximum tolerable concentration limits [88], e.g., mercury and cadmium. It has been recognised that even farmed earthworms can accumulate toxic substances, such as cadmium, above safe levels for animal feed [13]. The authors are not aware of any studies of the human health impacts of consuming a diet rich in foraged wild earthworms. However, in the authors' opinion, there is reasonable evidence that such a diet could be harmful and so should not be recommended unless starvation is the alternative.

As reported, without specific processing (i.e., creating sterilised defatted earthworm meal), farmed earthworms do not meet certain microbiological contamination standards for safe food [74]. Moreover, we, the authors, are not aware of any studies explicitly demonstrating that wild earthworms can meet modern standards of freedom from bacterial, fungal, parasitic, prion, or viral disease causing agents. Heat treatment is a common method for killing pathogens and so the processing methods discussed previously should remove the majority of biological threats [83]. Similarly, as sterilisation, in general, is used for near complete inactivation of microorganisms [89], sterilising methods other than the aforementioned one might be effective. Further experimental evidence in these areas is desirable.

Modern animal husbandry and meat processing techniques include provisions to prevent physical hazards such as bone shards, hypodermic needles, and hardware from damaged machinery entering food or feed [83]. Small scale facilities processing foraged earthworms for human consumption are reported in the media. Based on previous work on the processing of farmed earthworms into animal feed [14,15] it should be achievable to engineer a method for converting foraged earthworms into food that is free from physical contaminants.

A large-scale nuclear war is the most likely single event to cause an ASRS with or without GCIL [1] and could also have widespread ecological effects that make earthworms foraging unsuitable. Nuclear detonations can disperse radioactive material [83], known as fallout, across large tracts of land as well as starting firestorms that may induce toxic rain to fall in the surrounding area [90]. Foraging for earthworms in a contamination environment may be unsafe for workers due to the risk of direct radiation exposure. There may also be a risk for consumers of earthworms as, while earthworms are relatively resistant to the lethal effects of radiation, they can take up radioactive material from their environment [91,92]. However, radiation exposure of people is expected to be dominated by external direct doses rather than the ingested dose from irradiated food [93].

Ingestion of bioaccumulated chemical hazards is expected to present the greatest public health risk from foraging wild earthworms for food. Further research is required to address concerns of biological, physical and radioactive hazards, but these appear more solvable issues.

3.4.5 Foraging earthworms could reduce the future ecological and agricultural value of land

The activities of earthworms recycle nutrients through a food web and increase soil fertility. They are recognised to play a vital role in maintaining current agricultural production [94] and their relation to soil quality differs across the ecological categories [25]. An ASRS would cause severe disruption to all ecosystems on Earth, but society is likely to return to agricultural practices at some point in the future. A sustainable food solution for people should avoid impeding future production, and the possible effect of removing earthworms from large areas of land may warrant consideration. The sustainability needs might be met by earthworm farming, as nutritionally promising species such as *E. andrei* and *E. fetida* are extensively studied and utilised in vermicomposting and vermiculture settings [95]. Due to the aforementioned freeze-tolerance of cocoons (notably excluding *E. fetida* [69] and leaving *E. andrei* underresearched), dedicated units might be created after an ASRS onset, provided enough cocoons are stockpiled in advance or collected in time. Researching a food-production-optimised process for earthworm population growth (including species selection) and evaluating the feasibility and cost-effectiveness of such a process is out of this study's scope, but it is worth mentioning that nutritional values in adults of the same species might differ between wild and cultured ones [96,cf. 23].

3.4.6 Earthworms may suffer during capture, processing, and slaughter

There are considerable uncertainties regarding the capacity of whether invertebrates can suffer, and so whether it is beneficial to alleviate pain at the time of killing [94]. It is apparent that feeding a substantial fraction of the human populations with earthworms would entail the collection and slaughter of an enormous number of earthworms; thus, even a small degree of suffering per earthworm could be deemed significant. Some authors suggest there is evidence of nociceptors and endogenous nociception regulating chemicals in earthworms [97]. However, nociception may be necessary for pain, but it is not sufficient according to the definition of pain given by the International Association for the Study of Pain: "An unpleasant sensory and emotional experience associated with, or resembling that associated with, actual or potential tissue damage". There is a dearth of evidence regarding earthworm sentience [98] and a full review of the literature is outside the remit of this paper, so it will suffice to conclude that future works may want to consider the net effect on the welfare of all species if earthworms were to be harvested for food.

4 Conclusions

Based on the current scientific evidence, the estimated global population of earthworms could be a significant source of nutrition, especially protein, for the current human population. However, uncertainties around cost-effectiveness and food safety remain a barrier. Many techniques for harvesting wild earthworms are available and some have been described at length in the scientific literature, while others are less well characterised. Extrapolating data from academic studies on earthworm populations, neither chemical vermifuges nor electroshocking appear to be cost-effective methods for foraging enough earthworms to meet dietary needs. The methods used to forage wild earthworms for commercial purposes, worm grunting, and electroshocking in East Asia may be more cost-effective than implied by the results shown here, but further research is required to describe the efficiency of these techniques. If new data on earthworm biomass or foraging methods suggested much greater cost-effectiveness, an in-depth analysis of species-specific considerations would be warranted. Beyond the specific methods for foraging earthworms, the environmental changes associated with an ASRS with GCIL, global cooling, and radioactive pollution may reduce their effectiveness as a food source. As bioaccumulators, wild earthworms may contain heavy metals and other contaminants beyond safe levels for human consumption. These uncertainties should be considered in greater detail before global foraging of wild earthworms can be recommended as a resilient food source.

Supplementary material

Table S1: Calculations

Variable key	**Variable name**	**Calculation**
(a)	Total global earthworm biomass	= Earthworm-habitable land area (forest, shrubland pastures, arable) × mean earthworm biomass density
		= 1.03×10^{14} m^2 [20] × 51.18 $g \cdot m^{-2}$ [18]
		≈ 5.272×10^{15} g ≈ 5.3 billion tonnes
(b)	Mean earthworm dry matter percentage	= Mean of *L. terrestris*, *E. fetida*, and *A. chlorotica* earthworm dry matter percentage values from sources
		= Mean of 15.2% [22], 15.7% [23], and 20% [22]
		≈ 17.0%
(c)	Total global earthworm dry matter biomass	= *(b)* × *(a)*
		≈ 8.962×10^{14} g ≈ 900 million tonnes
(d)	Mean protein content of earthworm dry matter	= Mean of *E. andrei*, *E. fetida, H. euryaulos*, and *L. terrestris* earthworm dry matter percentage protein composition values from sources
		= Mean of 53.75% [11], 61.9%, 63%, and 64% [30]
		≈ 60.7%
(e)	Total nutritional protein in the global earthworm population	= *(c)* × *(d)*
		≈ 5.440×10^{14} g ≈ 540 million tonnes
(f)	Nutritional energy content of *E. fetida* earthworm dry matter	= Nutritional energy content of *E. fetida* earthworm meal / dry matter content of *E. fetida* earthworm meal

		= 2.99 kcal·g^{-1} / 0.906 [23]
		≈ 3.3 kcal·g^{-1}
(g)	Nutritional energy content of *E. andrei* earthworm dry matter	= (Nutritional energy content of *E. andrei* earthworm dry matter in kJ·hg^{-1}) / (kJ·kcal^{-1} conversion factor)
		= (2023.2 kJ·hg^{-1} [11]) / 4.184 kJ·kcal^{-1} [99]
		≈ 483.6 kcal·hg^{-1} ≈ 4.836 kcal·g^{-1}
(h)	Mean nutritional energy content of earthworm dry matter	= Mean of *E. fetida* and *E. andrei* earthworm dry matter nutritional energy values from sources
		= Mean of *(f)* and *(g)*
		≈ 4.068 kcal·g^{-1}
(i)	Total nutritional energy in the global earthworm population	= *(c)* × *(h)*
		≈ 3.646 × 10^{15} kcal ≈ 3.65 × 10^{15} kcal
(j)	Total nutritional energy in the global earthworm population expressed as equivalent to dry tonnes of carbohydrate	= *(i)* / calories per g of carbohydrate
		= *(i)* / 4 [100]
		≈ 9.115 × 10^{14} g ≈ 910 million tonnes
(k)	Fat content of *E. fetida* earthworm dry matter	= Fat content of *E. fetida* earthworm meal / dry matter content of *E. fetida* earthworm meal
		= 7.34% / 0.906 [23]
		≈ 8.102% ≈ 8.1%
(l)	Mean fat content of earthworm dry matter	= Mean of *E. fetida* and *E. andrei* earthworm dry matter fat content from sources
		= Mean of *(k)* and 19.3% [11]
		≈ 13.7%

(m)	Total nutritional fat in the global earthworm population	= *(c)* × *(l)*
		≈ 1.228×10^{14} g ≈ 122 million tonnes
(n)	Total nutritional fat in the global earthworm population in kcal	= *(m)* × kcal content per g of fat
		= *(m)* × 9 kcal·g^{-1} [101]
		≈ 1.105×10^{15} kcal ≈ 1.10×10^{15} kcal
(o)	Personal daily dietary fat requirement	= Personal daily nutritional energy requirement × proportion of energy intake recommended from dietary fats
		= 2100 kcal [38] × 0.15 [33]
		= 315 kcal
(p)	Personal daily protein requirement	= Amount of protein required per day per kg of body weight × average body weight of an adult human
		= 0.83 g·kg^{-1} [36] × 62 kg [37]
		= 51.46 g ≈ 51 g
(q)	Global daily protein requirement of the world human population	= World population × personal daily protein requirement
		= 8.07×10^{9} [34,35] × *(p)*
		≈ 4.15×10^{11}
(r)	Global daily nutritional energy requirement of the human world population	= World population × personal daily nutritional energy requirement
		= 8.07×10^{9} [34,35] × 2100 kcal [38]
		≈ 1.69×10^{13} kcal
(s)	Global daily nutritional fat requirement for the human population	= *(r)* × recommended percentage of daily energy from fat
		= *(r)* × 15% [33]

		$\approx 2.54 \times 10^{12}$ kcal
(t)	Potential number of days worth of nutritional protein there are for the world human population in the global earthworm resource	= *(e)* / *(q)*
		≈ 1310
(u)	Potential number of days worth of nutritional energy there are for the world human population in the global earthworm resource	= *(i)* / *(r)*
		≈ 216 ≈ 220
(v)	Potential number of days worth of nutritional fat there are for the world human population in the global earthworm resource	= *(n)* / *(s)*
		≈ 435 ≈ 440
(w)	Mass of fresh earthworms necessary to meet the daily personal protein requirement	= *(p)* / *(d)* / *(b)*
		≈ 498.7 g ≈ 500 g
(x)	Mean area of land required to harvest the daily personal protein requirement	= *(w)* / mean earthworm biomass density
		= *(w)* / 51.18 $\text{g} \cdot \text{m}^{-2}$ [18]
		≈ 9.744 ≈ 10 m^2
(y)	Total volume of soil excavated to extract the global earthworm population	= Earthworm-habitable land area (forest, shrubland pastures, arable) × depth of soil
		= 1.03×10^{14} m^2 [20] × 0.35 m
		$\approx 3.61 \times 10^{13}$ m^3

(z)	Volume of soil excavated to extract enough earthworms to meet the personal daily protein requirement	= *(x)* × 0.35
		≈ 3.410 ≈ 3.41 m^3
(aa)	Mass of soil excavated to extract enough earthworms to meet the personal daily protein requirement	= *(z)* × density of soil
		= *(z)* × 1500 $kg \cdot m^{-3}$ [102]
		≈ 5115 ≈ 5120 kg
(ab)	Time taken to sort the mass of soil excavated to extract enough earthworms to meet the personal daily protein requirement	= *(aa)* / extraction efficiency of mechanical sort / rate of mechanical sorter
		= *(aa)* / 0.8379 / 21.2 $kg \cdot min^{-1}$ [43]
		≈ 288 min ≈ 5 hr
(ac)	Number of peoples' daily protein requirements that could be met by a mechanical soil sorter in a day	= Number of minutes in a day / *(ab)*
		≈ 5.0
(ad)	Ratio fresh onion required to earthworm biomass extracted by the vermifuge method	= Mass of fresh onion used in vermifuge / biomass of earthworms extracted / area of land sampled
		= 700 g / 16 g/m^2 / 0.196 m^2 [49]
		≈ 223.2 g
(ae)	Volume of vermifuge solution required to harvest a personal daily protein requirement	= *(x)* / extraction efficiency of vermifuges × vermifuge application rate
		= *(x)* / 0.5 × 20 $L \cdot m^{-2}$
		≈ 389.8 ≈ 400 L
(af)	Electrical energy to meet	= Electrical energy required per g of foraged

	global annual protein requirement	earthworm protein × *(q)* × number of days in a year
		= 2.3 × 10^6 J [17] × *(q)* × 365
		≈ 3.48 × 10^{20} J
(ag)	Percentage of 2022 global electricity production required required to supply the global annual protein requirement with foraging earthworms by electroshocking	= *(af)* / global electricity production in 2022 × 100
		= *(af)* / 1.023 × 10^{20} J [86] × 100
		≈ 340.2% ≈ 340%

Supplementary figures

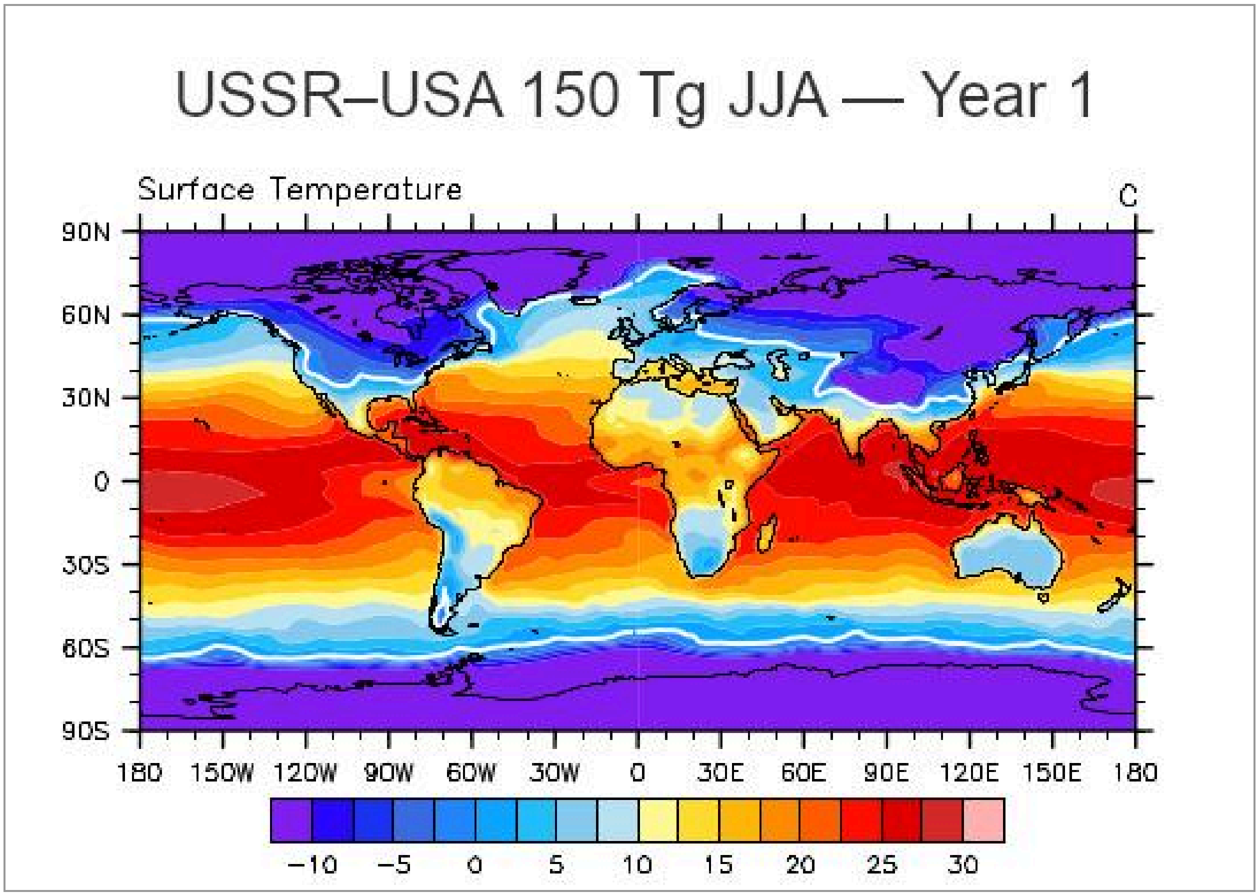
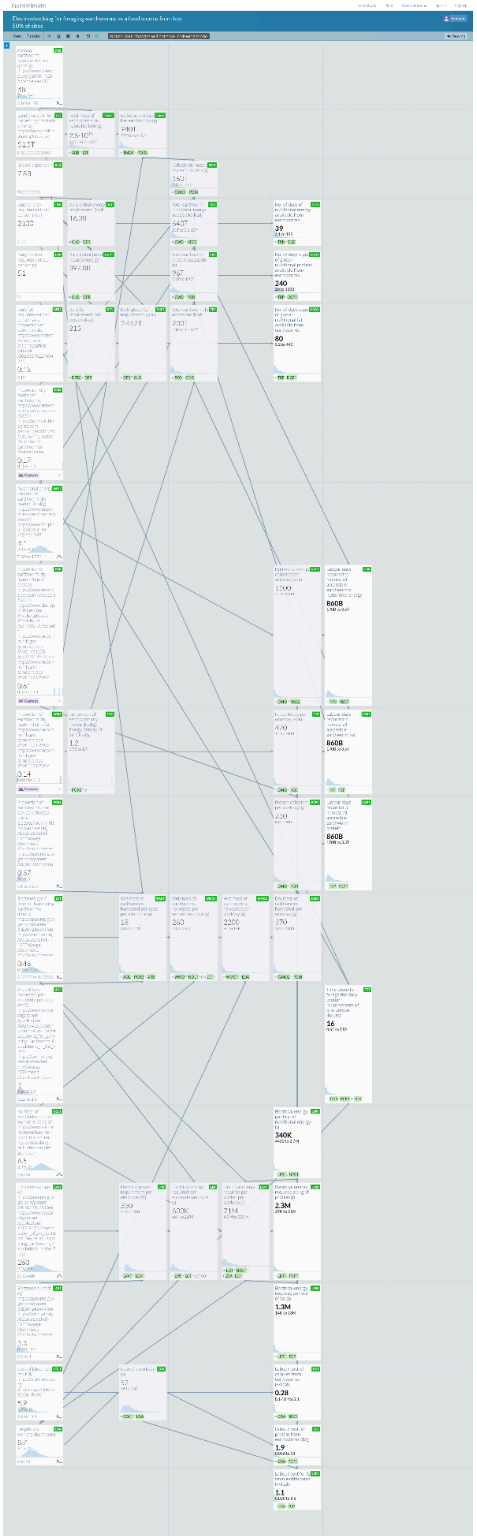


Figure S1: Predicted mean surface temperature of regions on Earth across June, July, and August (JJA) following a large-scale nuclear weapons exchange. This scenario assumes 150 million tons of soot injected into the stratosphere in May of the same year. The white line marks the edge of areas where mean surface temperature will fall below 0 ℃. In order to provide high resolution, very high and low values were truncated, based on Coupe, J.; Bardeen, C.G.; Robock, A.; Toon, O.B. Nuclear Winter Responses to Nuclear War Between the United States and Russia in the Whole Atmosphere Community Climate Model Version 4 and the Goddard Institute for Space Studies Model. E. J. Geophys. Res. Atmospheres 2019, 124, 8522–8543.



Guesstimate

Electroshocking for foraging earthworms as a food source from top 50% of sites

Figure S2: Overview of Guesstimate model calculations. Full model available online [17].

Author Contributions

Conceptualisation, H.M., J.M., and D.D.; Methodology, H.M., J.M., L.P., and R.P.; Software, H.M. and J.M.; Validation, H.M., J.M., L.P., R.P., and D.D.; Formal Analysis, H.M. J.M., and R.P.; Investigation, H.M., J.M., L.P., and R.P.; Resources, D.D.; Data Curation, H.M., J.M., L.P., and R.P.; Writing — Original Draft Preparation, H.M., J.M., and R.P.; Writing — Review & Editing, H.M., J.M., L.P., R.P., and D.D.; Visualisation, H.M. and J.M.; Supervision, D.D.; Project Administration, D.D.; Funding Acquisition, D.D.

Declaration of competing interests

The authors declare no conflict of interest.

Data Availability Statement

No new data were created or analysed in this study. Any source data used in calculations has been referenced. Data sharing is not applicable to this article.

Acknowledgements

The authors would like to thank Charles Bardeen and the team for global climate forecasts during a nuclear winter.

Funding

This research was supported by the Alliance to Feed the Earth in Disasters (ALLFED), and received no external funding.

References

1. Denkenberger, D.C.; Cole, D.D.; Abdelkhaliq, M.; Griswold, M.; Hundley, A.B.; Pearce, J.M. Feeding Everyone If the Sun Is Obscured and Industry Is Disabled. *Int. J. Disaster Risk Reduct.* **2017**, *21*, 284–290, doi:10.1016/j.ijdrr.2016.12.018.
2. Hyder, S.; Chhem, R.K.; Claes, F.; Karlsson, E.A. Pestilence and Famine: Continuing down the Vicious Cycle with COVID-19. *PLOS Pathog.* **2022**, *18*, e1010810, doi:10.1371/journal.ppat.1010810.
3. Tumelty, L.; Fa, J.E.; Coad, L.; Friant, S.; Mbane, J.; Kamogne, C.T.; Tata, C.Y.; Ickowitz, A. A Systematic Mapping Review of Links between Handling Wild Meat and Zoonotic Diseases. *One Health* **2023**, *17*, 100637, doi:10.1016/j.onehlt.2023.100637.
4. Pham, A.; García Martínez, J.B.; Brynych, V.; Stormbjorne, R.; Pearce, J.M.; Denkenberger, D.C. Nutrition in Abrupt Sunlight Reduction Scenarios: Envisioning Feasible Balanced Diets on Resilient Foods. *Nutrients* **2022**, *14*, 492, doi:10.3390/nu14030492.
5. Jehn, F.U.; Dingal, F.J.; Mill, A.; Harrison, C.; Ilin, E.; Roleda, M.Y.; James, S.C.; Denkenberger, D. Seaweed as a Resilient Food Solution after a Nuclear War. *Earths Future* **2024**, *12*, doi:https://doi.org/10.1029/2023EF003710.
6. Throup, J.; García Martínez, J.B.; Bals, B.; Cates, J.; Pearce, J.M.; Denkenberger, D.C. Rapid Repurposing of Pulp and Paper Mills, Biorefineries, and Breweries for Lignocellulosic Sugar Production in Global Food Catastrophes. *Food Bioprod. Process.* **2022**, *131*, 22–39, doi:10.1016/j.fbp.2021.10.012.
7. Rivers, M.; Hinge, M.; García Martínez, J.B.; Tieman, R.; Jaeck, V.; Butt, T.; Jehn, F.; Grillo, V.; Denkenberger, D. *Food System Adaptation and Maintaining Trade Greatly Mitigate Global Famine in Abrupt Sunlight Reduction Scenarios*; 2022;
8. García Martínez, J.B.; Pearce, J.M.; Throup, J.; Cates, J.; Lackner, M.; Denkenberger, D.C. Methane Single Cell Protein: Potential to Secure a Global Protein Supply Against Catastrophic Food Shocks. *Front. Bioeng. Biotechnol.* **2022**, *10*.
9. Sun, Z.; Jiang, H. Nutritive Evaluation of Earthworms as Human Food. In *Future Foods*; IntechOpen, 2017 ISBN 978-953-51-3552-4.
10. Conti, C.; Castrica, M.; Balzaretti, C.M.; Tedesco, D.E.A. Edible Earthworms in a Food Safety Perspective: Preliminary Data. *Ital. J. Food Saf.* **2019**, *8*, 7695, doi:10.4081/ijfs.2019.7695.
11. Kavle, R.R.; Nolan, P.J.; Carne, A.; Agyei, D.; Morton, J.D.; Bekhit, A.E.-D.A. Earth Worming—An Evaluation of Earthworm (Eisenia Andrei) as an Alternative Food Source. *Foods* **2023**, *12*, 1948, doi:10.3390/foods12101948.
12. Paoletti, M.G.; Buscardo, E.; VanderJagt, D.J.; Pastuszyn, A.; Pizzoferrato, L.; Huang, Y.-S.; Chuang, L.-T.; Millson, M.; Cerda, H.; Torres, F.; et al. Nutrient Content of Earthworms Consumed by Ye'Kuana Amerindians of the Alto Orinoco of Venezuela. *Proc. Biol. Sci.* **2003**, *270*, 249–257, doi:10.1098/rspb.2002.2141.
13. Byambas, P.; Hornick, J.L.; Marlier, D.; Francis, F. Vermiculture in Animal Farming: A Review on the Biological and Nonbiological Risks Related to Earthworms in Animal Feed. *Cogent Environ. Sci.* **2019**, 5, 1591328, doi:10.1080/23311843.2019.1591328.
14. Edwards, C.A. Production of Feed Protein From Animal Waste by Earthworms. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* **1985**, *310*, 299–307.
15. Musyoka, S.N.; Liti, D.M.; Ogello, E.; Waidbacher, H. Utilization of the Earthworm, Eisenia Fetida (Savigny, 1826) as an Alternative Protein Source in Fish Feeds Processing: A Review. *Aquac. Res.* **2019**, 50, 2301–2315, doi:10.1111/are.14091.

16. Catania, K.C. Worm Grunting, Fiddling, and Charming—Humans Unknowingly Mimic a Predator to Harvest Bait. *PLOS ONE* **2008**, *3*, e3472, doi:10.1371/journal.pone.0003472.
17. Henry Miller Electroshocking for Foraging Earthworms as a Food Source from Top 50% of Sites Available online: https://www.getguesstimate.com/models/23356 (accessed on 4 December 2023).
18. Phillips, H.R.P.; Guerra, C.A.; Bartz, M.L.C.; Briones, M.J.I.; Brown, G.; Crowther, T.W.; Ferlian, O.; Gongalsky, K.B.; van den Hoogen, J.; Krebs, J.; et al. Global Distribution of Earthworm Diversity. *Science* **2019**, *366*, 480–485, doi:10.1126/science.aax4851.
19. LavagnedOrtigue, O. (ESS) Land Use Statistics and Indicators (Food and Agriculture Organisation, United Nations, 2022).
20. Ritchie, H.; Roser, M. Land Use. *Our World Data* **2013**.
21. Carley, W.W. Water Economy of the Earthworm Lumbricus Terrestris L.: Coping with the Terrestrial Environment. *J. Exp. Zool.* **1978**, *205*, 71–78, doi:10.1002/jez.1402050110.
22. Roots, B.I. The Water Relations of Earthworms: II. Resistance to Desiccation and Immersion, and Behaviour When Submerged and When Allowed A Choice of Environment. *J. Exp. Biol.* **1956**, *33*, 29–44, doi:10.1242/jeb.33.1.29.
23. Sun, Z.; Liu, X.; Sun, L.; Song, C. Earthworm as a Potential Protein Resource. *Ecol. Food Nutr.* **1997**, *36*, 221–236, doi:10.1080/03670244.1997.9991517.
24. Bottinelli, N.; Hedde, M.; Jouquet, P.; Capowiez, Y. An Explicit Definition of Earthworm Ecological Categories – Marcel Bouché's Triangle Revisited. *Geoderma* **2020**, *372*, 114361, doi:10.1016/j.geoderma.2020.114361.
25. Fusaro, S.; Gavinelli, F.; Lazzarini, F.; Paoletti, M.G. Soil Biological Quality Index Based on Earthworms (QBS-e). A New Way to Use Earthworms as Bioindicators in Agroecosystems. *Ecol. Indic.* **2018**, *93*, 1276–1292, doi:10.1016/j.ecolind.2018.06.007.
26. Monroy, F.; Aira, M.; Domínguez, J.; Velando, A. Seasonal Population Dynamics of Eisenia Fetida (Savigny, 1826) (Oligochaeta, Lumbricidae) in the Field. *C. R. Biol.* **2006**, *329*, 912–915, doi:10.1016/j.crvi.2006.08.001.
27. Palm, J.; van Schaik, N.L.M.B.; Schröder, B. Modelling Distribution Patterns of Anecic, Epigeic and Endogeic Earthworms at Catchment-Scale in Agro-Ecosystems. *Pedobiologia* **2013**, *56*, 23–31, doi:10.1016/j.pedobi.2012.08.007.
28. De Wandeler, H.; Sousa-Silva, R.; Ampoorter, E.; Bruelheide, H.; Carnol, M.; Dawud, S.M.; Dănilă, G.; Finer, L.; Hättenschwiler, S.; Hermy, M.; et al. Drivers of Earthworm Incidence and Abundance across European Forests. *Soil Biol. Biochem.* **2016**, *99*, 167–178, doi:10.1016/j.soilbio.2016.05.003.
29. Schröder, B. Challenges of Species Distribution Modeling Belowground. *J. Plant Nutr. Soil Sci.* **2008**, *171*, 325–337, doi:10.1002/jpln.200700027.
30. Siyun Ding; Xiting Lin; Sanger He Earthworms: A Source of Protein. *J. Food Sci. Eng.* **2019**, *9*, doi:10.17265/2159-5828/2019.05.001.
31. WHO *Diet, Nutrition and the Prevention of Chronic Diseases*; WHO Technical Report Series 916. ISBN: 92-4-120916-X; Geneva, 2003; ISBN 92-4-120916-X.
32. WHO Interim Summary of Conclusions and Dietary Recommendations on Total Fat & Fatty Acids. **2008**, doi:https://www.who.int/nutrition/topics/FFA_summary_rec_conclusion.pdf.
33. García Martínez, J.B.; Alvarado, K.A.; Denkenberger, D.C. Synthetic Fat from Petroleum as a Resilient Food for Global Catastrophes: Preliminary Techno-Economic Assessment and Technology Roadmap. *Chem. Eng. Res. Des.* **2022**, *177*, 255–272, doi:10.1016/j.cherd.2021.10.017.
34. World Population Clock: 8.1 Billion People (LIVE, 2023) - Worldometer Available online: https://www.worldometers.info/world-population/ (accessed on 3 November 2023).
35. World Population Prospects - Population Division - United Nations Available online: https://population.un.org/wpp/ (accessed on 3 November 2023).

36. Joint FAO/WHO/UNU Expert Consultation on Protein and Amino Acid Requirements in Human Nutrition (2002 : Geneva, S.; Nations, F. and A.O. of the U.; Organization, W.H.; University, U.N. *Protein and Amino Acid Requirements in Human Nutrition : Report of a Joint FAO/WHO/UNU Expert Consultation*; World Health Organization, 2007; ISBN 978-92-4-120935-9.
37. Walpole, S.C.; Prieto-Merino, D.; Edwards, P.; Cleland, J.; Stevens, G.; Roberts, I. The Weight of Nations: An Estimation of Adult Human Biomass. *BMC Public Health* **2012**, *12*, 439, doi:10.1186/1471-2458-12-439.
38. Food and Nutrition Needs in Emergencies Available online: https://www.unhcr.org/uk/media/food-and-nutrition-needs-emergencies (accessed on 3 November 2023).
39. Darwin, Charles *The Formation of Vegetable Mould, through the Action of Worms, with Observations on Their Habits.*; Williams Clowes and Sons, 1881;
40. Darwin, Charles *On the Origin of Species by the Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life.*; Williams Clowes and Sons, 1859;
41. Rhea-Fournier, D.; González, G.; Rhea-Fournier, D.; González, G. Methodological Considerations in the Study of Earthworms in Forest Ecosystems. In *Forest Ecology and Conservation*; IntechOpen, 2017 ISBN 978-953-51-3090-1.
42. Jiménez, J.J.; Lavelle, P.; Decaëns, T. The Efficiency of Soil Hand-Sorting in Assessing the Abundance and Biomass of Earthworm Communities. Its Usefulness in Population Dynamics and Cohort Analysis Studies. *Eur. J. Soil Biol.* **2006**, *42*, S225–S230, doi:10.1016/j.ejsobi.2006.07.031.
43. Lin, J.; zhao, shuai; Yuan, Q. A Novel Technology for Separating Live Earthworm from Vermicompost: Experiment, Mechanism Analysis, and Simulation. *Waste Manag.* **2021**, *131*, 50–60, doi:10.1016/j.wasman.2021.05.031.
44. Mitra, O.; Callaham, M.A.; Smith, M.L.; Yack, J.E. Grunting for Worms: Seismic Vibrations Cause Diplocardia Earthworms to Emerge from the Soil. *Biol. Lett.* **2009**, *5*, 16–19, doi:10.1098/rsbl.2008.0456.
45. Singh, J.; Singh, S.; Vig, A.P. Extraction of Earthworm from Soil by Different Sampling Methods: A Review. *Environ. Dev. Sustain.* **2016**, *18*, 1521–1539, doi:10.1007/s10668-015-9703-5.
46. Public Health England Compendium of Chemical Hazards.
47. Evans, A.C.; Guild, W.J.McL. Studies on the Relationships Between Earthworms and Soil Fertility: I. Biological Studies in the Field. *Ann. Appl. Biol.* **1947**, *34*, 307–330, doi:10.1111/j.1744-7348.1947.tb06367.x.
48. Singh, J.; Singh, S.; Bhat, S.A.; Vig, A.P.; Schädler, M. Eco-Friendly Method for the Extraction of Earthworms: Comparative Account of Formalin, AITC and Allium Cepa as Extractant. *Appl. Soil Ecol.* **2018**, *124*, 141–145, doi:10.1016/j.apsoil.2017.11.007.
49. Steffen, G.P.K.; Antoniolli, Z.I.; Steffen, R.B.; Jacques, R.J.S.; dos Santos, M.L. Earthworm Extraction with Onion Solution. *Appl. Soil Ecol.* **2013**, *69*, 28–31.
50. Gutiérrez-López, M.; Moreno, G.; Trigo, D.; Juárez, E.; Jesús, J.B.; Díaz Cosín, D.J. The Efficiency of Earthworm Extraction Methods Is Determined by Species and Soil Properties in the Mediterranean Communities of Central-Western Spain. *Eur. J. Soil Biol.* **2016**, *73*, 59–68, doi:10.1016/j.ejsobi.2016.01.005.
51. Pelosi, C.; Chiron, F.; Dubs, F.; Hedde, M.; Ponge, J.-F.; Salmon, S.; Cluzeau, D.; Nélieu, S. A New Method to Measure Allyl Isothiocyanate (AITC) Concentrations in Mustard—Comparison of AITC and Commercial Mustard Solutions as Earthworm Extractants. *Appl. Soil Ecol.* **2014**, *80*, 1–5, doi:10.1016/j.apsoil.2014.03.005.
52. Zaborski, E.R. Allyl Isothiocyanate: An Alternative Chemical Expellant for Sampling Earthworms. *Appl. Soil Ecol.* **2003**, *22*, 87–95, doi:10.1016/S0929-1393(02)00106-3.

53. Satchell, J.E. An Electrical Method of Sampling Earthworm Populations. *Soil Zool.* **1955**, *356*, 364.
54. Schmidt, O. Appraisal of the Electrical Octet Method for Estimating Earthworm Populations in Arable Land. *Ann. Appl. Biol.* **2001**, *138*, 231–241, doi:10.1111/j.1744-7348.2001.tb00107.x.
55. Weyers, S.; Schomberg, H.; Hendrix, P.F.; Spokas, K.; Endale, D. Construction of an Electrical Device for Sampling Earthworm Populations in the Field. *Appl. Eng. Agric.* **2008**, *24*, doi:10.13031/2013.24492.
56. Thielemann, U.D.B. Electrical Earthworm Trap Using the Octet Method 1987.
57. Applebome, P. RECALL IS ORDERED FOR WORM PROBES. *N. Y. Times* 1993.
58. Phillips, H. R. P. et al.(2019). Global Distribution of Earthworm Diversity (Version 1.1) . Dataset Available at iDiv Data Repository.
59. Greed in Front of Many People Using Electric Shock to Kill Earthworms - Vietnam.Vn Available online: https://www.vietnam.vn/en/ham-loi-truoc-mat-nhieu-nguoi-dan-dung-kich-dien-tan-diet-giun-dat/ (accessed on 8 November 2023).
60. Real Minimum Wages Available online: https://stats.oecd.org/index.aspx?DataSetCode=RMW (accessed on 8 November 2023).
61. R. Jokkonen, N. Ghosheh Rest Periods: Definitions and Dimensions, International Labour Organisation.
62. International Labour Organisation Convention C030 - Hours of Work (Commerce and Offices) Convention, 1930 (No. 30) 1930.
63. Denkenberger, D.; Pearce, J.; Taylor, A.R.; Black, R. Food without Sun: Price and Life-Saving Potential. *foresight* **2019**, *21*, 118–129, doi:10.1108/FS-04-2018-0041.
64. Coupe, J.; Bardeen, C.G.; Robock, A.; Toon, O.B. Nuclear Winter Responses to Nuclear War Between the United States and Russia in the Whole Atmosphere Community Climate Model Version 4 and the Goddard Institute for Space Studies ModelE. *J. Geophys. Res. Atmospheres* **2019**, *124*, 8522–8543, doi:10.1029/2019JD030509.
65. Reynierse, J.H. Effects of Temperature and Temperature Change on Earthworm Locomotor Behaviour. *Anim. Behav.* **1968**, *16*, 480–484, doi:10.1016/0003-3472(68)90043-2.
66. Singh, J.; Schädler, M.; Demetrio, W.; Brown, G.G.; Eisenhauer, N. Climate Change Effects on Earthworms - a Review. *Soil Org.* **2019**, *91*, 114–138, doi:10.25674/so91iss3pp114.
67. Greiner, H.G.; Stonehouse, A.M.T.; Tiegs, S.D. Cold Tolerance among Composting Earthworm Species to Evaluate Invasion Potential. *Am. Midl. Nat.* **2011**, *166*, 349–357.
68. Edwards C.A., Bohlen P.J. *Biology and Ecology of Earthworms | SpringerLink, p.426*; Chapman and Hall: London, 1996;
69. Daugbjerg, P. Temperature and Moisture Preferences of Three Earthworm Species (Oligochaeta, Lumbricidae). *Pedobiologia* **1988**, *32*, 57–64, doi:10.1016/S0031-4056(23)00216-0.
70. Holmstrup, M. Overwintering Adaptations in Earthworms: The 7th International Symposium on Earthworm Ecology · Cardiff · Wales · 2002. *Pedobiologia* **2003**, *47*, 504–510, doi:10.1078/0031-4056-00220.
71. Holmstrup, M.; Overgaard, J. Freeze Tolerance in Aporrectodea Caliginosa and Other Earthworms from Finland. *Cryobiology* **2007**, 55, 80–86, doi:10.1016/j.cryobiol.2007.06.001.
72. Bundy, J.G.; Ramløv, H.; Holmstrup, M. Multivariate Metabolic Profiling Using 1H Nuclear Magnetic Resonance Spectroscopy of Freeze-Tolerant and Freeze-Intolerant Earthworms Exposed to Frost. *CryoLetters* **2003**, *24*, 347–358.
73. Patricia M. Barcelo Production and Utilization of Earthworms as Feeds for Broilers in the Phillipines. *Tropicultura* **1988**, *6*, 21–24.
74. Tedesco, D.E.A.; Castrica, M.; Tava, A.; Panseri, S.; Balzaretti, C.M. From a Food Safety Prospective: The Role of Earthworms as Food and Feed in Assuring Food Security and in

Valuing Food Waste. *Insects* **2020**, *11*, 293, doi:10.3390/insects11050293.

75. Erratum for the Report "Global Distribution of Earthworm Diversity" by H. R. P. Phillips, C. A. Guerra, M. L. C. Bartz, M. J. I. Briones, G. Brown, T. W. Crowther, O. Ferlian, K. B. Gongalsky, J. van Den Hoogen, J. Krebs, A. Orgiazzi, D. Routh, B. Schwarz, E. M. Bach, J. Bennett, U. Brose, T. Decaëns, B. König-Ries, M. Loreau, J. Mathieu, C. Mulder, W. H. van Der Putten, K. S. Ramirez, M. C. Rillig, D. Russell, M. Rutgers, M. P. Thakur, F. T. de Vries, D. H. Wall, D. A. Wardle, M. Arai, F. O. Ayuke, G. H. Baker, R. Beauséjour, J. C. Bedano, K. Birkhofer, E. Blanchart, B. Blossey, T. Bolger, R. L. Bradley, M. A. Callaham, Y. Capowiez, M. E. Caulfield, A. Choi, F. V. Crotty, A. Dávalos, D. J. Diaz Cosin, A. Dominguez, A. E. Duhour, N. van Eekeren, C. Emmerling, L. B. Falco, R. Fernández, S. J. Fonte, C. Fragoso, A. L. C. Franco, M. Fugère, A. T. Fusilero, S. Gholami, M. J. Gundale, M. Gutiérrez López, D. K. Hackenberger, L. M. Hernández, T. Hishi, A. R. Holdsworth, M. Holmstrup, K. N. Hopfensperger, E. Huerta Lwanga, V. Huhta, T. T. Hurisso, B. V. Iannone III, M. Iordache, M. Joschko, N. Kaneko, R. Kanianska, A. M. Keith, C. A. Kelly, M. L. Kernecker, J. Klaminder, A. W. Koné, Y. Kooch, S. T. Kukkonen, H. Lalthanzara, D. R. Lammel, I. M. Lebedev, Y. Li, J. B. Jesus Lidon, N. K. Lincoln, S. R. Loss, R. Marichal, R. Matula, J. H. Moos, G. Moreno, A. Morón-Ríos, B. Muys, J. Neirynck, L. Norgrove, M. Novo, V. Nuutinen, V. Nuzzo, M. Rahman P, J. Pansu, S. Paudel, G. Pérès, L. Pérez-Camacho, R. Piñeiro, J.-F. Ponge, M. I. Rashid, S. Rebollo, J. Rodeiro-Iglesias, M. Á. Rodríguez, A. M. Roth, G. X. Rousseau, A. Rozen, E. Sayad, L. van Schaik, B. C. Scharenbroch, M. Schirrmann, O. Schmidt, B. Schröder, J. Seeber, M. P. Shashkov, J. Singh, S. M. Smith, M. Steinwandter, J. A. Talavera, D. Trigo, J. Tsukamoto, A. W. de Valença, S. J. Vanek, I. Virto, A. A. Wackett, M. W. Warren, N. H. Wehr, J. K. Whalen, M. B. Wironen, V. Wolters, I. V. Zenkova, W. Zhang, E. K. Cameron, N. Eisenhauer. *Science* **2020**, 369, eabd9834, doi:10.1126/science.abd9834.
76. James, S.W.; Csuzdi, C.; Chang, C.-H.; Aspe, N.M.; Jiménez, J.J.; Feijoo, A.; Blouin, M.; Lavelle, P. Comment on "Global Distribution of Earthworm Diversity." *Science* **2021**, *371*, eabe4629, doi:10.1126/science.abe4629.
77. MAURIZIO G. PAOLETTI University of Padova, Padova, Italy; FEDERICO GAVINELLI University of Padova, Padova, Italy; TIZIANO GOMIERO Independent scholar; MARCEL BOUCHÉ Laboratory of Zooecology of soil, INRA, Monpellier Cedex, France; GIUSEPPE CONCHERI Department of Agronomy, Food, Natural resources, Animals and Environment, University of Padova, Padova, Italy; CSABA CSUZDI Department of Zoology, Eszterházy Károly University, Eger, Hungary; LUCA DORIGO Friulian Museum of Natural History, Udine, Italy; LEANDRO A. DREON University of Padova, Padova, Italy; SILVIA FUSARO University of Padova, Padova, Italy; SAM JAMES Sustainable Living Department, Maharishi University, Fairfield, Iowa, USA; et al. Mapping the Global Distribution of Earthworm Diversity: A Laudable Initiative Deserving a Better Approach 2019.
78. R.J. Blakemore Nature Article to Commemorate Charles Darwin's Birthday on 12th February. *VermEcology* 2017.
79. Lee, K.E. (Kenneth E. *Earthworms : Their Ecology and Relationships with Soils and Land Use*; Sydney ; Orlando : Academic Press, 1985; ISBN 978-0-12-440860-9.
80. Most Worms Charmed Available online: https://www.guinnessworldrecords.com/world-records/most-worms-charmed (accessed on 8 November 2023).
81. Capturing Earthworms by Electric Shock Poses Environmental Hazards Available online: https://vietnamnews.vn/environment/1582676/capturing-earthworms-by-electric-shock-poses-environmental-hazards.html (accessed on 8 November 2023).
82. VIETNAM: Earthworm Electrocution Is Destroying The Environment For China Trade. *AsiaViews* 2023.
83. FAO *Introduction and Control of Food Hazards – Section 1*; FAO Good Hygiene Practices (GHP)

and Hazard Analysis and Critical Control Point (HACCP) Toolbox for Food Safety; FAO: Rome, Italy, 2023;

84. Richardson, J.B.; Görres, J.H.; Sizmur, T. Synthesis of Earthworm Trace Metal Uptake and Bioaccumulation Data: Role of Soil Concentration, Earthworm Ecophysiology, and Experimental Design. *Environ. Pollut.* **2020**, *262*, 114126, doi:10.1016/j.envpol.2020.114126.
85. Nfor, B.; Fai, P.B.A.; Tamungang, S.A.; Fobil, J.N.; Basu, N. Soil Contamination and Bioaccumulation of Heavy Metals by a Tropical Earthworm Species (Alma Nilotica) at Informal E-Waste Recycling Sites in Douala, Cameroon. *Environ. Toxicol. Chem.* **2022**, *41*, 356–368, doi:10.1002/etc.5264.
86. FAO and UNEP. *Global Assessment of Soil Pollution: Report. Rome.*; 2021; ISBN 978-92-5-134469-9.
87. Scutarașu, E.C.; Trincă, L.C. Heavy Metals in Foods and Beverages: Global Situation, Health Risks and Reduction Methods. *Foods* **2023**, *12*, 3340, doi:10.3390/foods12183340.
88. FAO and WHO General Standard for Contaminants and Toxins in Food and Feed 2022.
89. Li, X.; Farid, M. A Review on Recent Development in Non-Conventional Food Sterilization Technologies. *J. Food Eng.* **2016**, *182*, 33–45, doi:10.1016/j.jfoodeng.2016.02.026.
90. Shapiro, Charles; Harvey, Ted Radioactive Fallout. In *The Medical Implications of Nuclear War*; National Academies Press (US), 1986.
91. Sutou, S. Black Rain in Hiroshima: A Critique to the Life Span Study of A-Bomb Survivors, Basis of the Linear No-Threshold Model. *Genes Environ.* **2020**, *42*, 1, doi:10.1186/s41021-019-0141-8.
92. Hasegawa, M.; Ito, M.T.; Kaneko, S.; Kiyono, Y.; Ikeda, S.; Makino, S. Radiocesium Concentrations in Epigeic Earthworms at Various Distances from the Fukushima Nuclear Power Plant 6 Months after the 2011 Accident. *J. Environ. Radioact.* **2013**, *126*, 8–13, doi:10.1016/j.jenvrad.2013.06.006.
93. Maystrenko, T.; Rybak, A. Radium Uptake by Earthworms E. Fetida after Exposure to Contaminated Soil. *J. Environ. Radioact.* **2023**, *257*, 107085, doi:10.1016/j.jenvrad.2022.107085.
94. Cooper, J.E. Anesthesia, Analgesia, and Euthanasia of Invertebrates. *ILAR J.* **2011**, 52, 196–204, doi:10.1093/ilar.52.2.196.
95. Domínguez, J. Earthworms and Vermicomposting. In *Earthworms - The Ecological Engineers of Soil*; Ray, S., Ed.; IntechOpen, 2018 ISBN 978-1-78923-397-1.
96. Bhorgin Lourdumary, A.J.; Uma, K. Nutritional Evaluation of Earthworm Powder (Lampito Mauritii). *J. Appl. Pharm. Sci.* **2012**, 3, 82–84, doi:10.7324/JAPS.2013.30316.
97. Jones, R.C. Science, Sentience, and Animal Welfare. *Biol. Philos.* **2013**, *28*, 1–30, doi:10.1007/s10539-012-9351-1.
98. Opinion: Estimating Invertebrate Sentience Available online: https://rethinkpriorities.org/publications/opinion-estimating-invertebrate-sentience (accessed on 28 November 2023).
99. Butcher, K.S.; Crown, L.D.; Gentry, E.J. *The International System of Units (SI) - Conversion Factors for General Use*; 0 ed.; National Institute of Standards and Technology: Gaithersburg, MD, 2006; p. NIST SP 1038;
100. Slavin, J.; Carlson, J. Carbohydrates1. *Adv. Nutr.* **2014**, 5, 760–761, doi:10.3945/an.114.006163.
101. Thomas, L.M.; Holub, B.J. Nutritional Aspects of Fats and Oils. In *Technological Advances in Improved and Alternative Sources of Lipids*; Kamel, B.S., Kakuda, Y., Eds.; Springer US: Boston, MA, 1994; pp. 16–49 ISBN 978-1-4615-2109-9.
102. Dirt and Mud - Densities Available online: https://www.engineeringtoolbox.com/dirt-mud-densities-d_1727.html (accessed on 3 November 2023).
103. Ritchie, H.; Rosado, P.; Roser, M. Electricity Mix. *Our World Data* **2023**.