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## Opinion

# Small Millets for Enduring Food Security Amidst Pandemics

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Food security is an ongoing problem, and current staple foods are not sufficient to overcome challenges such as the present COVID-19 pandemic. We propose here that small millets have the potential to become new staple crops, especially in hunger hotspots. Currently, the absence of intensification of millet farming, lack of deployment of genetic tools for trait improvement, and the need for optimization of storage and supply chains limit crop production. We highlight a roadmap to strengthen small millet cultivation, such as identifying varieties suitable for particular environments and targeting trait improvement using genetic and genomic approaches. These approaches will help to combat hunger and malnutrition and also economically benefit the farmers and stakeholders involved in small millet cultivation amidst the ongoing pandemic.

## COVID-19 Drives the Hunger Index Exponentially

Among the 7.8 billion global population, 820 million people experience **chronic hunger** (see [Glossary](#)), and these include 135 million people surviving in acute food insecurity zones across 55 countries ([www.un.org/](http://www.un.org/)). The United Nations (UN) Food and Agriculture Organization (FAO) predicts that the ongoing COVID-19 pandemic will increase this number as developing countries are double-hit by disease and hunger ([www.fao.org/2019-ncov/q-and-a/](http://www.fao.org/2019-ncov/q-and-a/)). Disruptions in global supply chains, economic consequences (i.e., loss of jobs and incomes), the ban on the export of agricultural commodities, and price increases are the major reasons for this crisis. Although much attention is being given to the development of vaccines, therapeutic molecules, and preventive measures to combat COVID-19, the invisible threat to the lives and livelihoods of marginal populations through hunger and malnutrition remains largely unaddressed. The focus of the 2019 **Global hunger index** on 'The Challenge of Hunger and Climate Change' underlines the impacts of changing climates on agriculture that include crop failures owing to problems such as seasonal fluctuations, increased insect and pest attacks, and broad-spectrum infection by potential pathogens ([www.globalhungerindex.org/](http://www.globalhungerindex.org/)). In this scenario, a prevalent pandemic adds to the crisis by limiting access to food for the marginal population. This will have an enduring effect on human capital, particularly for children. Countries such as India, Sudan, Ethiopia, Somalia, Yemen, Bhutan, and Sri Lanka, where >31% of children under 5 years of age are stunted and 15% are too thin for their height, will be worst affected owing to the combined effects of disease and hunger (<https://data.unicef.org/>). Supplying food grains is an immediate measure to aid the affected population, whereas devising long-term plans to prevent such challenges is the need of the hour. That said, the possibility of a second wave of COVID-19 in the near future should not be ignored [1]. In such a case, the UN World Food Programme predicts (UN-WFP; <https://insight.wfp.org/>) that death due to lack of food would outnumber deaths caused by disease infection. One non-conventional approach to address food insecurity and ensure preparedness to face future catastrophes is to mainstream the production of crops that are marginally cultivated in regions with limited resources. Also known as **underutilized crops**, these crops are grown in arid- and semi-arid regions where poor soil fertility, limited rainfall, and less attack of insect pests prevail.

## Highlights

Over-reliance on a small number of major cereals impacts on the food and nutritional security of the global population, particularly during abnormal situations.

The ongoing COVID-19 pandemic challenges the lives and livelihood of marginal communities by limiting their access to these crops.

Diversification of food crops is necessary to address food and nutritional security, and promoting the cultivation of alternative crops in marginal areas is imperative.

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In addition, these crops are nutritionally dense and, in many adverse environmental conditions, have the potential to diversify diets and overcome food and nutritional shortages for marginal communities [2,3]. The importance of crop diversity and of mainstreaming underutilized crops that could serve as **functional foods** has been pointed out before; however, identifying the best candidates of underutilized crops and deploying crop improvement strategies to release better varieties is still in a nascent stage. Mayes *et al.* [4] proposed five criteria for identifying the best potential underutilized crops, namely adaptability to the environment, market value of the produce, taste and texture, value-addition, and reduced requirements for agricultural inputs. These criteria prioritize small millets or minor millets as a potential source of food and nutritional security that could rescue the poorest and most vulnerable segments of the population during situations such as the current pandemic. Other plant species, including tubers, legumes, and leafy vegetables, also fall within the criteria of underutilized species; however, emphasis is given to small millets because they are capable of reducing the overdependence on major cereals. Three major cereals, namely rice, wheat, and maize, cater for up to 60% of the global food requirements, and this is one of the plausible causes of food and nutritional inadequacies in the hunger hotspots where these crops are largely imported for consumption. Millets, although cultivated marginally in those regions, have the potential to address these inadequacies if their area of cultivation is increased and crop improvement strategies are devised and deployed.

### Small Millets Offer a Sustainable Alternative to Major Staple Crops

'Small millets' is a generic term that denotes the coarse cereals. It includes finger millet (*Eleusine coracana*), foxtail millet (*Setaria italica*), proso millet (*Panicum miliaceum*), barnyard millet (*Echinochloa crus-galli*), kodo millet (*Paspalum scrobiculatum*), little millet (*Panicum sumatrense*), teff (*Eragrostis tef*), fonio (*Digitaria exilis*), Job's tears (*Coix lacryma-jobi*), guinea millet (*Brachiaria deflexa*), and browntop millet (*Urochloa ramosa*) [5,6] (Figure 1). Small millets were widely cultivated as traditional crops in rain-fed areas of semi-arid regions around the globe; however, the introduction of **cash crops** restricted their cultivation to particular areas [5–9]. Although small millets belong to the same family (Poaceae) of major cereals [e.g., rice (*Oryza sativa*), wheat (*Triticum aestivum*), maize (*Zea mays*), and sorghum (*Sorghum bicolor*)], these crops are superior to major cereals in terms of agroecological traits, nutritional quality, and the potential to ensure the immediate demands of food security. In terms of agroecological traits, millets have better water-use and nitrogen-use efficiencies that enable them to withstand water-limiting conditions [10]. For example, foxtail millet requires ~250 g of water to produce 1 g of dry biomass, whereas wheat and maize require ~450 and 500 g, respectively [11]. Similarly, a study in finger millet reported a requirement of nitrogen fertilizer as low as 20–60 kg/ha for better productivity [12]. Small millets are also rich in micro- and macro-nutrients, total protein, fiber, and **resistant starch**. For instance, finger millet is rich in calcium (~364 mg per 100 g) and potassium (~320 mg per 100 g), and little millet and barnyard millet have high iron contents (~10–18 mg per 100 g). The total protein is high in foxtail millet and barnyard millet (>10%), and crude fiber is rich in barnyard millet, little millet, foxtail millet, and fonio (~7–14%) [13]. Further, the majority of small millets are gluten-free, and therefore facilitate the preparation of low **glycemic index** products [14,15].

Compared to major cereals, small millets are capable of meeting the immediate need for food security in at least five important ways. (i) Small millets ensure subsistence and income to the marginal population because yield loss or the influence of other external factors (i.e., climate, rainfall, and disease) that impact on productivity is minimal compared to major cereals. Although the area of production and yield of small millets are significantly less than for major cereals, millets could provide a better gross return (the sum total of income from grain and straw), net return (the difference between gross return and cost of cultivation), and benefit–cost ratio (ratio of gross return to the total cost of cultivation). (ii) The sustainability of agriculture can be ensured by

### Glossary

**Cash crops:** crops that are cultivated for their commercial value and not for consumption by the farmer or farming community. These crops contribute to the economic growth of the regions in which they are produced and marketed.

**Chronic hunger:** hunger arising from persistent inability to meet dietary energy requirements that lasts for a significant period of time during the year.

**Climate-resilient traits:**

characteristics that confer the ability to adapt, reorganize, and withstand the stresses imposed by climate change.

**Functional foods:** dietary items that beneficially modulate one or more targeted functions in the body in addition to providing nutrients and energy [32]. These foods can regulate or enhance biological defense mechanisms, reduce the risk of disease, control physical or mental disorders, and slow the aging process.

**Global hunger index:** a system devised to track hunger at global, regional, and national levels. The scores are calculated based on four indicators, namely undernourishment, child wasting, child stunting, and child mortality.

**Glycemic index:** the ratio of increase in blood glucose caused by a dietary intake to that of glucose (standard reference) for a period of 2 h.

**Resistant starch:** one of the three forms of dietary carbohydrates, namely, rapidly digestible, slowly digestible, and resistant starch. These complex molecules resist acidic digestion in the stomach and are not absorbed in the small intestine. When passed to the large intestine, they are catabolized by the gut microbiota into simple sugars.

**Speed breeding:** a method to accelerate the life cycle of plants by modulating the duration of the day–light cycle and the intensity of light to achieve a higher number of generations per year.

**Underutilized crops:** indigenous species grown in the arid- and semi-arid regions by marginal populations around the globe. These crops, otherwise called minor, orphan, or neglected, have not received much research attention and remain largely unexplored.



**Figure 1. Characteristic Features of Small Millets.** The grain morphologies of small millets are shown along with their key traits and specific usages.

cultivating small millets because they have reduced dependence on synthetic fertilizers (fossil fuel-derived nitrogen fertilizers), pesticides, weedicides, and insecticides. The global warming potential (GWP) and carbon equivalent emission (CEE) of rice and wheat are the highest among the cereals. The GWP (CO<sub>2</sub> eq/ha) of wheat and rice are 4 and 3.4 tons, respectively, and their CEEs (kg C/ha) are 1000 and 956, respectively [16]. However, the carbon footprints of small millets could be comparatively lower than those of major cereals [17], although exact values are not available to date. (iii) Small millet cultivation and use decrease the over-reliance on the major cereals that are limited in number. Of note, the majority of the global population relies on rice and wheat as their staple food, and the intervention of small millets could reduce this dependence. (iv) Another advantage is the food quality, where millets are established to be highly nutritious with no compromise in taste and texture that are considered to be essential traits for consumer preference. (v) Small millets can contribute to ensuring diversity in food. Of the tens of thousands of plant species known on Earth, ~7000 species are edible, among which only 20% cater for 90% of global food requirements [18–20]. Rice, wheat, and maize make up 60% [21] of all staple crops, resulting in a monotonous diet. This lack of diversity also increases the risk of disruption in production and supply during calamities such as COVID-19, exacting a heavy toll on humankind.

In addition to small millets, underutilized tubers and legumes could add to food and dietary diversification. Among tubers, cassava (*Manihot esculenta*), sweet potato (*Ipomoea batatas*), and taro (*Colocasia esculenta*) are cultivated in African countries, where the tubers, corms, and leaves of these species are consumed as food by economically deprived classes [22]. Arrowroot (*Maranta arundinacea*), Indian shot (*Canna indica*), gonala (*Dioscorea spicata*), purple yam (*D. alata*), air potato (*D. bulbifera*), and elephant foot (*Amorphophallus paeoniifolius*) are a few notable tuber crops that are cultivated in arid- and semi-arid regions [5,22]. In the case of legumes, bambara groundnut (*Vigna subterranea*), cowpea (*V. unguiculata*), rice bean (*V. umbellata*), adzuki beans (*V. angularis*), winged bean (*Psophocarpus tetragonolobus*), jack bean (*Canavalia ensiformis*), kidney bean (*Phaseolus vulgaris*), lima bean (*P. lunatus*), faba bean (*Vicia faba*), horsegram (*Macrotyloma uniflorum*), and velvet bean (*Mucuna pruriens*) are meagerly

produced in hunger-prone regions [20,23], and these legumes have the potential to develop food self-sufficiency among the population. Therefore, while underscoring the importance of small millets in solving hunger and related issues, the collective role of these tubers and legumes as well as millets in ensuring food and nutritional security should not be overlooked.

### Mainstreaming Millets for Ensuring Multiple Securities during Pandemics

The pertinent role of small millets is not limited to addressing food and nutritional well-being, and it potentially extends to boosting immunity, providing fodder for cattle, improving biodiversity, and protecting the livelihood of farmers. Although there is no direct evidence that millets boost immunity (see Outstanding Questions), researchers suggest that the presence of minerals, vitamins, and antioxidants in the right composition in the grains would optimize the functioning of the immune system [13,15]. The high amount of resistant starch in these millets promotes restrained catabolism of complex carbohydrates into simple sugar by the gut microbiota, leading to slow and sustained release of glucose into the bloodstream [24,25], thus providing a healthy diet. This would also ensure the supply of up to 2000–3000 calories per person per day [25]. These traits underline the importance of mainstreaming small millets. The regions of small millet cultivation around the globe predominantly overlap with the hunger hotspots identified by the UN (Figure 2). Therefore, prioritizing millet cultivation in these regions is feasible, but will require the development of a roadmap for improving beneficial traits, deploying better agronomic practices, and optimizing storage and supply chains. The hotspots, where other species are being grown, require the identification of suitable millet species for cultivation and adequate training to be given to the farmers.

The identification of a variety suitable for a given location depends on climatic factors, soil fertility, irrigation requirements, and the availability of human resources. Release of suitable seed materials for cultivation could be facilitated through the germplasm repositories that are present worldwide; however, trait improvement with respect to the target location may be necessary to achieve better agronomic values of the produce (Box 1). Modern genetic tools and biotechnological

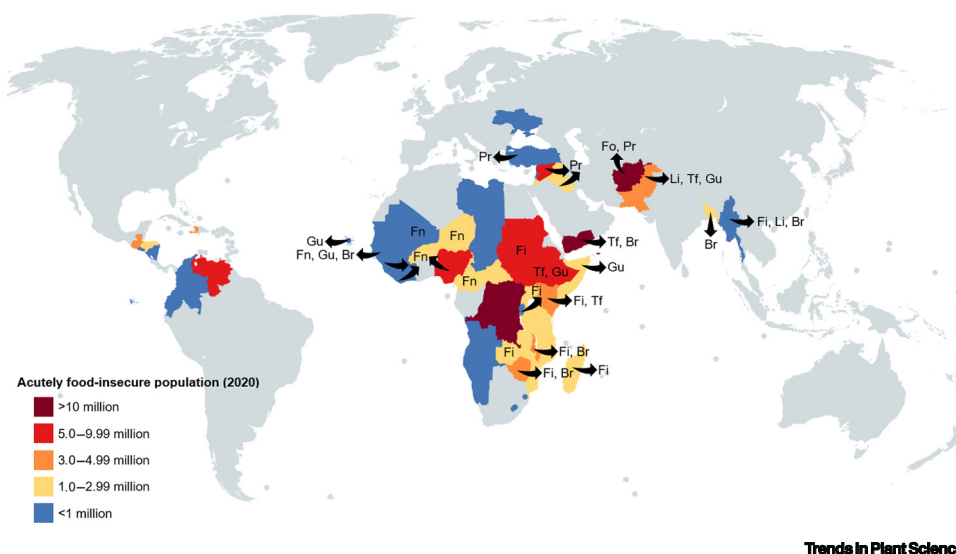


Figure 2. An Integrated Map of Hunger Hotspots Spanning 55 Countries with Acutely Food-Insecure Populations (Year 2020) and the Small Millet Cultivated in Those Regions. Abbreviations: Ba, barnyard millet; Br, browntop millet; Fi, finger millet; Fn, fonio; Fo, foxtail millet; Gu, guinea millet; Jt, Job's tears; Ko, kodo millet; Li, little millet; Pr, proso millet; Tf, teff.

### Box 1. Recent Progress in Millet Research

Genetic and genomic resources are imperative for crop improvement, where genetic resources serve as the primary input for breeding and research, and genomic resources facilitate the efficient characterization of genetic resources and their utilization in crop improvement. In terms of genetic resources, 164 447 cultivated and wild germplasms of small millets are conserved in genebanks worldwide ([www.fao.org/](http://www.fao.org/)). However, the majority of the germplasms belong to finger millet, foxtail millet, and proso millet, whereas the representation of other small millets is minimal. Several germplasms were lost in the process of shifting to cash crops, and an intensive drive will be necessary to conserve the remaining material before this is permanently lost. In terms of genomic resources, whole-genome sequencing (WGS) of foxtail millet, green foxtail, finger millet, barnyard millet, and teff [26–30] was performed to identify the novel genes, alleles, and quantitative trait loci underlying yield-determining, agronomic, and climate-resilience traits (reviewed in [33]). The WGS data are available in databases including Phytozome (<https://phytozome.jgi.doe.gov/>), Gramene ([www.gramene.org/](http://www.gramene.org/)), and EnsemblPlants (<https://plants.ensembl.org/>). This has facilitated the development of large-scale, genome-wide molecular markers [34], the construction of high-density maps [35–37], and the identification of genomic regions governing key traits for use in breeding programs [38–42].

Given the availability of these resources, small millet breeding programs presently focus on resolving production constraints. Lodging and seed-shattering are major problems in millet cultivation [43], and in kodo millet, mutation-breeding has shown promising results to develop improved non-lodging varieties [44]. In addition, there are specific genetic traits of interest that have received less research attention. Notably, genetic determinants of grain micronutrient content were studied to a limited extent in small millets. In foxtail millet, Jaiswal *et al.* [40] identified 74 marker–trait associations for 10 micronutrient traits through GWAS. Recently, Puranik *et al.* [42] performed GWAS in finger millet to identify 418 SNPs linked to micronutrient content. These studies should be extended to enable genomics-assisted breeding for the development of improved varieties with high micronutrient content. Resistant starch content is another important trait specific to millet grain that awaits scientific intervention to unravel its genetics and genomics [45]. Other prospective areas of research in millets as compared to major cereals include C<sub>4</sub> photosynthetic traits [46,47] and tolerance to multiple environmental stresses [48,49], the development and characterization of male sterility systems [33,50], enhancing the shelf-life (rancidity issues) [51], reducing grain antinutrients including phytates, phenols, tannins, and enzyme inhibitors [52–54], and addressing the issues of lodging and seed-shattering [43,55]. A recent study also reported an increased incidence of insect pests, wherein up to 150 different species were found to attack millets at different growth and developmental stages [31]. Identifying resistant germplasms and investigating them using omic tools (Figure 3) will facilitate the development of elite lines with enhanced resistance to insect pests.

interventions could assist in the process, and the availability of genome and transcriptome sequence information for a few small millets, including foxtail millet, finger millet, barnyard millet, and teff [26–30], would expedite the genetic improvement programs. Good agronomic practices include streamlined irrigation for water management, soil tillage and amendments, and active crop rotation. Although millets require less attention to these parameters owing to their **climate-resilient traits**, practicing such methods enable higher yield and minimize the effects of crop failure [5,6]. Recently, an increase in insect pests attacking the millets at different stages of their growth and development has been reported [31]. Studying the biology of such pests, their mode of action, and the host defense responses underlying tolerance to insect pests will be essential for developing tolerant varieties. Optimizing integrated pest management strategies will also assist in mitigating the effects of insect pests.

Post-harvest processing and storage are bottlenecks in the large-scale production of seed grains, although, in the case of major cereals, streamlined processes and equipment are available to ensure processing and storage with minimal wastage; however, such equipment for harvesting and/or threshing is not available for all the small millets. Because the grain morphologies and architectures of all millets are unique, crop-specific technologies need to be developed and implemented. Long-term storage of millet grains requires precautionary measures such as temperature beyond optimum to prevent sprouting or rotting, and millet grain tends to become rancid owing to its higher lipid content, and therefore, storage strategies to be devised to avoid large-scale loss of valuable produce. These storage facilities serve as a reserve for the people to rely on during natural calamities or future pandemic situations, and thus prevent inflation of global hunger and child malnutrition indices. Established supply chains will ensure the transportation of

the agricultural outputs that would economically benefit the farmers and stakeholders involved in small millet cultivation.

### Concluding Remarks and Future Perspectives

Small millets have been referred to as ‘smart foods’ or ‘nutri-cereals’ because they are better adapted to diverse environmental conditions through water-use and nitrogen-use efficiencies, tolerance to insect pests and diseases, and resistance to environmental stresses. The climate-resilient features and nutritional profiles of small millets have been widely studied, indicating that millets could be the staple crops of choice in hunger-stricken areas identified by the UN-FAO and UN-WFP. These regions are heavily affected by malnutrition, undernutrition, and premature deaths owing to the non-availability of food in abnormal situations. The WFP anticipates that the number of people encountering acute food insecurity will double as a result of the ongoing pandemic, and this emphasizes the urgent need for agricultural reforms to provide a long-term solution for this population group ([www.wfp.org/publications/2020-global-report-food-crises](http://www.wfp.org/publications/2020-global-report-food-crises)). Food scarcity does not seem to be an issue at this point in time, given the adequate stocking of major staples; however, ensuring nutritional security is equally important to assure the well-being of the vulnerable population. Given this, we have emphasized the timely need to mainstream small millets in the areas that are most susceptible to food shortages, and have outlined a roadmap to expedite the process. In addition, an important component will involve technological interventions to address some of the current shortcomings of small millets (Figure 3). For example, millet grain is rich in lipids that result in rancidity during storage. The development of lines with optimal lipid contents will be essential to promote enhanced shelf-life. Second, millet grain contains significant levels of antinutrients, including phytic acid that inhibits the bioavailability of nutrients (e.g., uptake of iron) to the human system. Elite lines with low phytic acid content could be developed using genomics-assisted breeding or transgene-based approaches. Whole-genome sequencing and resequencing of existing germplasm collections will facilitate the identification of genes and novel allelic variants for trait discovery and subsequent use in trait improvement. Precise editing of pathway genes through the CRISPR/Cas9 approach also

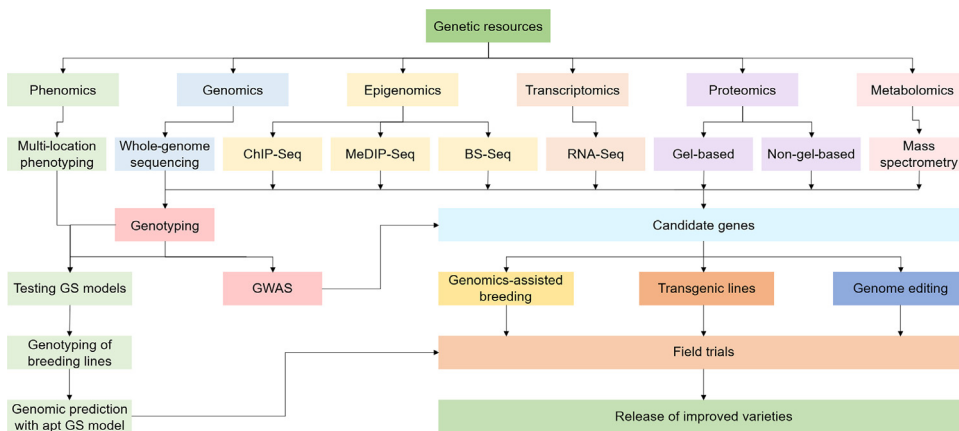
### Outstanding Questions

There is some indication that whole grains strengthen the immune system, but any underlying mechanism is so far unknown. New research should address this question with an emphasis on the composition of millet grains and their potential ability to stimulate biological processes.

Currently, data on millet species are held by several agricultural databases, including FAOSTAT. However, the area of production, yield, and production quantity of individual small millet species are not readily available. These data are essential for drawing the roadmap for mainstreaming small millet cultivation.

Popularization of millets among the population – that largely relies on major cereals, including rice, wheat, and maize – will remain a difficult task, and novel approaches will be necessary to ensure success.

Genetic improvement of millets requires adequate funding and research infrastructure. Such laboratories and international collaborations exist for cash crops; however, small millet research is far behind the progress being made in major cereals.



Trends in Plant Science

**Figure 3. A Multi-Omic Approach for Genetic Improvement of Millet Species.** Integration of data gained from phenomics, genomics, epigenomics, transcriptomics, proteomics, and metabolomics would pinpoint candidate genes that could be manipulated using either transgene-based (overexpression/silencing) or genome-editing approaches to develop improved varieties. Integration of phenomic and genomic data either through genome-wide association studies or genomic selection will expedite breeding of improved varieties. Abbreviations: BS-Seq, bisulfite-sequencing; CHIP-Seq, chromatin immunoprecipitation and deep sequencing; GS, genomic selection; GWAS, genome-wide association studies; MeDIP-Seq, methylated DNA immunoprecipitation and deep sequencing.

facilitates the development of better varieties, and exploiting such next-generation genomic approaches in underutilized crops should be promoted. Accelerated crop improvement programs using techniques such as **speed breeding** are not currently practiced in millets; however, this has potential to minimize breeding timelines and facilitate the early release of varieties. The UN-FAO has announced the year 2023 as 'International Year of Millets', recognizing the potential of this crop. By that time, the intervention of government and non-governmental bodies in initiating or reviving millet farming may be expected to incentivize increased millet production. This could achieve success in combating hunger and malnutrition among the vulnerable population in any future aberrant conditions (see Outstanding Questions).

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