sensitivity, providing further confidence in the extremely high energies reported for the γ-rays produced by the PeVatron candidates.

For one of these candidates, the authors detected γ-rays with energies as high as 1.4 PeV, coming from the direction of the constellation Cygnus. This finding will catch the attention of many researchers and will surely be examined critically by scientists inside and outside the LHAASO Collaboration. Intriguingly, both the Tibet ASγ Collaboration[12] and the High-Altitude Water Cherenkov (HAWC) Collaboration[13] reported γ-ray emission exceeding 0.1 PeV from this region of the sky. The HAWC researchers studied the surface brightness of the region and connected the emission to the Cygnus OB2 star cluster, where powerful shock waves generated by strong stellar winds might accelerate particles to PeV energies. In the future, the LHAASO Collaboration could carry out similar studies to constrain the maximum power of cosmic-ray acceleration in star clusters.

New telescopes will come online in the next few years, and others are in the planning phase. The Cherenkov Telescope Array[14] is a ground-based observatory that will be run by a multinational consortium at sites in Chile and the Canary Islands, Spain. Another group of astrophysicists plans to build the Southern Wide-field Gamma-ray Observatory[15] in South America. With its large field of view, this instrument would be ideally positioned to survey huge swathes of the Southern Hemisphere's sky, which includes an excellent view of the Galactic Centre. These next-generation instruments will search for signs of PeVatrons and other extreme, possibly unexpected structures to learn more about the nature and transport of matter and energy in the Universe.

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Food

Unearthing hidden hunger in Africa

Ken E. Giller & Shamie Zingore

A diet containing insufficient micronutrients can harm human health. Maps that pinpoint areas of Africa associated with micronutrient-poor grains now offer a way to target interventions that tackle such deficiencies. **See p.71**

Access to sufficient safe, nutritious food for a healthy diet is a basic human right, and eradicating hunger lies at the heart of the global sustainability agenda. As we move towards the United Nations Food Systems Summit later this year, it is imperative that the debate about global food security shifts from a narrow focus on providing enough calories to consideration of how to provide the right balance of foods needed. A challenge related to this, and one not often placed in the limelight, is the issue of 'hidden hunger', the deficiency of specific micronutrients (minerals and vitamins), which is prevalent in many countries of sub-Saharan Africa. On page 71, Gashu *et al.*[1] present maps of Ethiopia and Malawi that highlight hotspots at greatest risk of human micronutrient deficiency associated with local cereal intake. This information, obtained by measuring the mineral content of cereal grains and the soils in which they were grown, enlarges the range of options available when selecting interventions to enhance human health.

Micronutrient deficiencies negatively affect the growth and development of plants, animals and people alike. Women and children are disproportionally affected[2] as a result of their dietary needs and because of the socio-economic and cultural disadvantages that they can face. If hidden hunger causes health problems during early childhood and an individual's learning ability is impaired[3], this can have lifelong negative consequences. As with all health problems, correct diagnosis is the first step towards an effective remedy. However, by the time health disorders due to micronutrient deficiencies become apparent, the damage has been done, so it is essential to develop methods that can predict where problems will probably occur.

Direct assessment of human micronutrient deficiency requires blood sampling, which is a complex task for large-scale population studies spanning wide geographical areas. Instead, dietary intake of micronutrients is commonly assessed indirectly on the basis of a typical diet and with the use of food-composition tables giving the micronutrient content of foods. However, this approach is confounded by local variability in food quality.

The link between soil micronutrient deficiencies and dietary effects on human health is a subject of growing research interest owing to the possible interconnections between soil, plants, animals and human health. The empirical evidence for this link in the regions most severely affected by micronutrient deficiencies is variable and not well established. Could we predict the likelihood of the existence of hidden hunger on the basis of soil properties? Gashu and colleagues, part of a large team of soil scientists and statisticians, have addressed that question on a national scale across Ethiopia and Malawi. They sampled cereal grains from thousands of farmers' fields, at locations selected to be representative of large geographical areas.

The authors overcame major logistical challenges to carry out this work over huge areas, within the short time frame around harvest time. The grain samples obtained were ground and analysed to determine their concentrations of calcium, iron, selenium and zinc. These are key micronutrients that are often deficient in the human diet.

The cereal crops most commonly consumed in Ethiopia are wheat and teff (*Eragrostis tef*; Fig. 1), a tiny-seeded grain. The authors' study of Ethiopia indicated that wheat and teff could contribute up to one-quarter of the recommended dietary calcium needed. By contrast, they found that maize (corn), the staple cereal in Malawi, could provide only 3% or less of the dietary calcium needed. Maize also provided less than one-quarter of the selenium requirement, half of the iron and three-quarters of the zinc requirement. The mapping exercise revealed a high variability in grain micronutrient concentrations, with an increased risk that this grain intake, if part of a diet lacking diversity, will lead to human micronutrient deficiencies in some regions of the countries studied.

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ALAMY

Figure 1 | Harvesting teff (*Eragrostis tef*) in Ethiopia.

At first glance, one might expect that these patterns could be mapped simply by looking for soils deficient in micronutrients, given that African soils have already been mapped in detail. Unfortunately, it is not that simple. A key problem is determining the biological availability (bioavailability) of these elements, which are generally only sparingly soluble.

Despite decades of research, we lack robust tests for measuring the bioavailable concentrations of micronutrients in soil. Why is this? First, the bioavailability of micronutrients depends on their chemistry and oxidation state — in oxygenated (aerobic) soil, many micronutrients are present as insoluble compounds. Second, plants take up nutrients selectively. Some essential nutrients are actively absorbed even though they are present in extremely low concentrations in the soil. Plants are also able to avoid taking up toxic amounts of nutrients. A key example of this is iron, which is abundant in soils — iron oxides give tropical soils their beautiful deep orange colour. Most of this iron is in an insoluble form, which plants absorb in only small quantities.

Once inside plants, nutrients can be transported in various ways, which affects whether they are key components of plant material that is eaten. Plants absorb calcium only in locations close to the growing root tip because this micronutrient cannot cross a cell layer (the suberized endodermis) that is found in the mature root. Calcium and iron transport occurs only in xylem vessels, which carry them towards the growing leaves and tip of the plant, and they cannot be remobilized and used elsewhere in the plant. Certain plant parts, for example grains, or storage organs such as tubers, are high in starch formed from sugars that are transported there by the phloem tissue. Leafy vegetables, alongside animal-sourced foods (such as meat, milk and eggs), are therefore crucial for providing calcium and iron in our diets, because these micronutrients cannot easily be taken up into grains.

Staple foods, such as cereals, roots and tubers, which are eaten in high quantities to provide energy, contain only small amounts of micronutrients. Moreover, during the processing that refines flour, micronutrients in grain can be removed, and some cereals and other foods contain molecules, such as phytates, that reduce micronutrient bioavailability. So the bioavailability of nutrients in the human gut is also a major factor, and the cereal grains studied by Gashu *et al.* are only one part of our complex diets.

Assessment of a soil's underlying bedrock could provide clues to micronutrient content, but agricultural management hampers the effectiveness of using such assessments. Human activities can have positive or negative effects on soil. Efforts such as adding animal manure boost the accumulation of organic matter and improve soil quality, whereas continuous cropping without replenishing nutrients reduces soil fertility. In extreme cases, the soil carbon content can vary threefold among the fields of a single smallholder farm[4]. Soil organic matter is a key source of micronutrients, and also helps to regulate soil properties that improve the availability of micronutrients for uptake by crops[5]. Beyond the level of the farm, loss of forests in Ethiopia has led to a reduction in dietary diversity[6].

The detailed maps generated by Gashu *et al.* provide a strong basis for the future targeting of interventions to address hidden hunger. The authors report that information about soil pH offered a way to predict the selenium concentrations in grain. However, the relationship between pH and zinc concentrations in grain was less consistent. The level of soil organic matter was positively related to zinc concentrations in grain. It therefore seems likely that analysis of the soils in which the crops are grown cannot offer a substitute for the direct analysis of micronutrient concentrations in grain. Ethiopia and Malawi are located at opposite ends of the East African Rift Valley and have relatively young soils created by the uplift of tectonic plates. A stronger prevalence of micronutrient deficiencies might be associated with the older, more heavily weathered soils that cover much of the African continent.

There is clear evidence for a link between grain micronutrient concentrations and human food intake, but the direct effects of such dietary boosts to health are more difficult to establish. For example, in addition to the issues of bioavailability discussed, it is worth considering that much of what people consume comes from local markets, and not from their own fields.

Hidden hunger might be tackled through a variety of targeted interventions that follow on from the work of Gashu and colleagues. Soil enrichment through balanced fertilizer use, in combination with the management of soil organic matter, is the basis of agronomic biofortification[7]. Considerable research has been devoted to developing genetic approaches for biofortification, by identifying crop varieties enriched in micronutrients, and the discovery of mechanisms by which plants can accumulate micronutrients also shows promise[8]. A more direct path to alleviating deficiencies is the direct supplementation of foodstuffs with micronutrients. However, perhaps the best prospects for alleviating micronutrient deficiencies are offered by diversifying diets to increase the consumption of legumes, vegetables and animal-sourced foods that contain high levels of minerals and vitamins.

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