Healthy Soil & Nutritious Food

The science behind the role of soil health in the nutrient content of food, and its contribution to human health.

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The New Climate.

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Any discussion of the role of plant contribution to human nutrition must recognize that plants would “prefer” that we did not eat them. (Plants don’t think about us and have no preferences — but it is easy to think things through if we pretend that they do). When we eat their leaves, stems, root, fruit, or seeds — we are decreasing their potential to grow and reproduce. Many plants contain toxins that wage constant chemical warfare against bacteria, fungi, insects, and animals that try to eat them — including us. Of course, we have evolved metabolic means of tolerating some of these toxins and we have developed technology to overcome others.

Cooking decreases many toxins though more elaborate processes are required for some foods. We've even learned to like the taste of some toxins, including in citrus fruit.

Beginning at least 10,000 years ago, humans began domesticating plants to meet *our needs*, and one effect has been to select against plants detrimental to our health — which is often correlated with making them less bitter, sweeter, and less fibrous. This process has made the plants less hardy and more in need of our protection.

Plants did not evolve to be nutritious to humans — it was the opposite. We've spent the last 10,000 years trying to undo that evolution. The irony is that some of these plant defenses are now known to confer benefits on humans. So how can we maximise those benefits, while avoiding the pitfalls?

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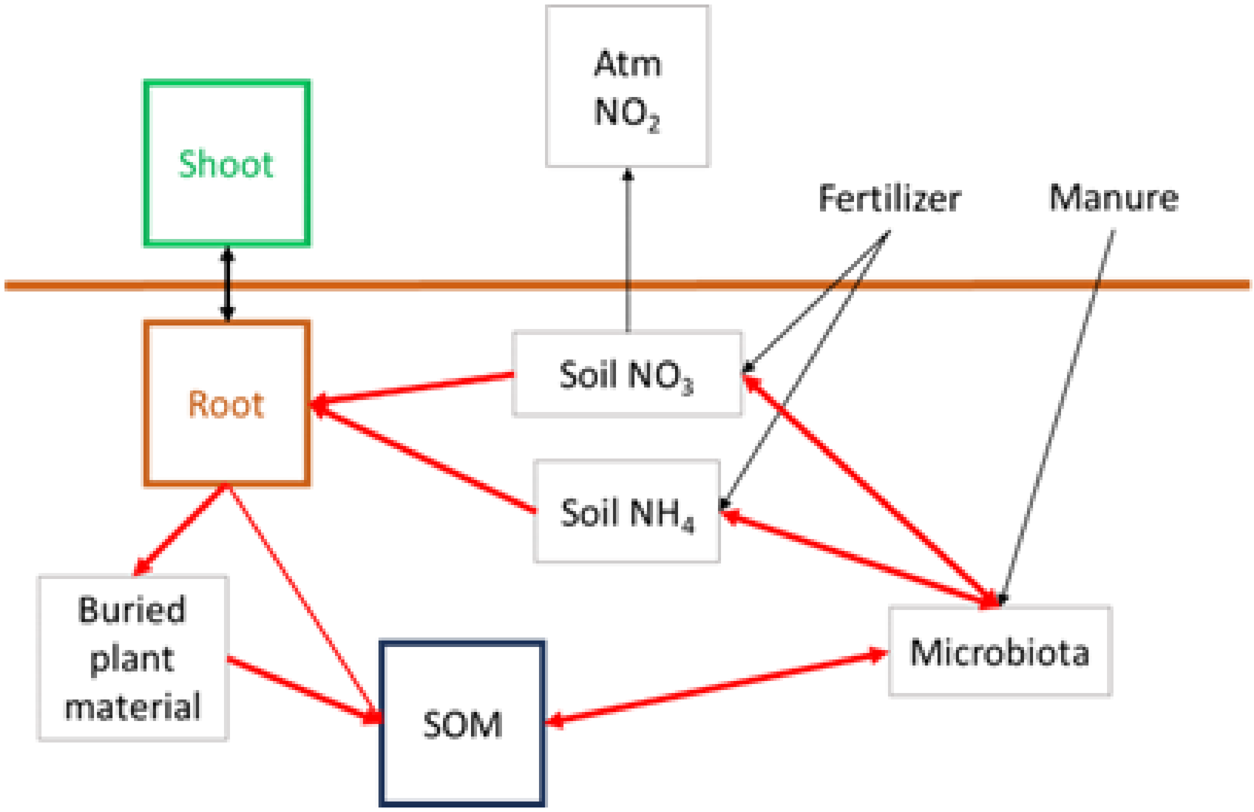
We work with more than one version of nutrition. The basic version relates to adequate consumption of the chemical elements and compounds we need to survive. This version is about avoiding starvation and must incorporate the fact that an adult can survive weeks without food — unlike air or water, we carry a buffer of stored calories and other nutrients.

Broadly, this means we require protein, minerals, and vitamins and other specific nutrients as well as an adequate supply of calories. A full understanding of nutrition is beyond the scope of this article, but the key point is that there are the following three states:

1. gross malnutrition characterized by insufficient calories and major nutrients;
2. adequate nutrition characterized by no limitations to health;
3. optimal nutrition characterized by increased resilience and functionality. Thus, nutrition science has established minimal “daily” requirements for adequate nutrition but not optimal ones; it is hard to define optimal.

One of the clearest intersections between plant and human nutrition is nitrogen. Human life depends on the ability of plants to convert inorganic nitrogen into organic nitrogen — mostly in the form of protein (and to be more exact — amino acids). One of the great triumphs of the 20th century was the development of the Haber process to reduce atmospheric nitrogen for use in fertilizer. This enabled a massive increase in calorie production through higher yields mostly eliminating gross malnutrition. And subsequent work began to identify and overcome the other barriers to adequate nutrition. From a soil health perspective, soils that have been in use for a long time are often depleted in nitrogen and soil organic matter (SOM, a source of nitrogen) — so the first step in restoring soil health is often adding nitrogen fertilizer. A second step is to increase SOM to get a soil nitrogen cycle going, illustrated in the schematic below.



While fertilizers can be added directly to the soil and taken up without intermediation, normally there is intense competition between plants and the microbiota for nitrogen, so most nitrogen gets pulled into the cycle rapidly. Soil microbes are adapted to their soil conditions and help ensure that nitrogen is in a suitable form (NO3 or NH4) for the soil. As seems always to be the case, SOM has a prime role, in this case as the largest pool of stable nitrogen in the soil. As described before, nitrogen is removed with the crop and must be restored if good yield (and nutrient supply to humans) is to be maintained.

Photosynthesis results in two things: fixed carbon that an be converted to various uses and latent energy that can be released by respiration. All organisms seek to optimize energy use, and THE prime issue for any organism is how to maximize the probability of survival in the next generation. For plants, the more energy placed in seeds the better, but plants are not just carbohydrate or lipid. There are the enzymes needed to transform the carbohydrate/lipid, the vitamin co-factors required for metabolism, and the minerals needed for metabolic catalysis and structure stabilization.

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The carbohydrate is the metabolically “cheap” stuff, so any carbon diverted to the rest of this stuff detracts from the energy passed down to the next generation. Evolution has resulted in methods to optimize the energy used. For example in wheat, the essential proteins required for germination are placed in the fertilized seed almost immediately and a stock of storage protein is added to get the future seedling started. From that point, seeds are mostly filled with starch. The consequence of this is that wheat can be high protein or high yield (exceptions to be explained shortly). From our perspective, high yield means more calories but less non-caloric nutrition. High protein might be more nutritious but also means less wheat grain overall and fewer calories. Thus, there is a conflict in desires in the real, energy constrained world. Though the example of wheat is used here, such balancing between “energy” stores and protein (or other nutrients) are common.

This is an ecological constraint adaptive for real, stressful conditions. Wheat plants grown in hydroponics with controlled lighting, temperature, and water availability show both high yield and high protein. It is also known that boosting nitrogen supply at the right time also boosts seed protein. Bringing us back to the nitrogen cycle and soil health. Wheat plants are tall during the ideal time to add nitrogen, so it is hard for a farmer to drive through a field to deliver a fertility treatment (whether synthetic or natural) without destroying the crop. A healthy soil is constantly cycling nitrogen from SOM to microbes to soil and so forth. An active nitrogen cycle during the key point in wheat plant development can supply the nitrogen boost required to boost protein concentration in the seeds. Indeed, soils with higher concentrations of SOM in the upper layers of soil had higher wheat grain protein concentrations.

A slightly different dynamic applies to acquisition of minor mineral nutrients by plants. It is common for these to be present as ions adsorbed on the soil mineral matrix and effectively insoluble in the soil water. Plants may stimulate release of these ions directly by secreting organic acids (citric, tartaric, malic, etc.) into the soil. The acids “extract” the minerals into the soil water where it is available to plants. Some of these acids are consumed by soil microbes and used for food — and the bacteria extract the minerals (especially easy in a biofilm) for their own use. When they die, the minerals become available to plants.

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Some bacteria and fungi form more exclusive interactions with plant roots. For example, Frankia, Funneliformis, and Rhizobia form mutually beneficial relationships with plants. Frankia and Rhizobia reduced atmospheric nitrogen in exchange for carbohydrates and organic acids. Funneliformis is an example of a wide class of Actinomyces that colonize the surface or intercellular spaces of roots to promote water and nutrient uptake. Mycorrhizae (to use one general term for fungi used this way) are often used in tree planting and forest restoration as a kind of prebiotic for the soil. Nurturing the existing soil microbiome is not very difficult — just add “food.” Changing the microbiome is very difficult as the microbiome is well adapted to local conditions across many seasons.

This creates a bit of a chicken-and-egg situation. Healthy plants help promote a healthy soil microbiome and a healthy soil microbiome is needed to create healthy plants. A healthy ecosystem requires exchanges of energy and materials, where every organism must optimize the exchange for themselves. A sacrifice of carbon in exchange for mineral nutrients maximizes the chance of survival in the next generation; plants outsource mineral acquisition to the microbiome and pay them in reduced carbon.

An another example of the drive to conserve biological energy is the ability to harvest nutrients directly from the soil. Experiments showed that multiple crops absorb vitamins B1 and B12 from soils supplemented with manure. The manure is rich in these vitamins, and by absorbing them directly the plants save energy for other things. A soil with a complex web of nutrient cycling may produce compounds “desired” by plants and in the interest of minimal energy expenditure, they are taken up.

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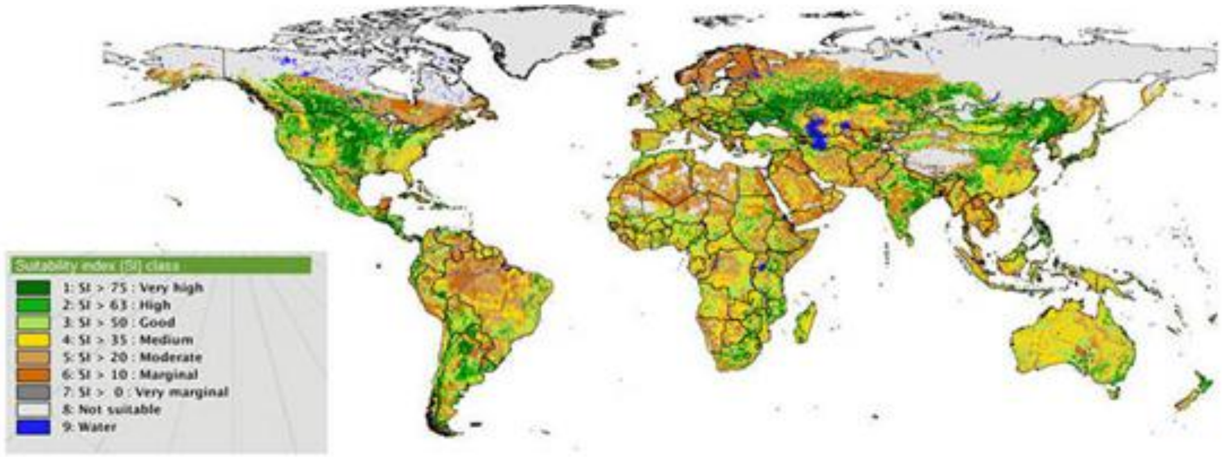
For most of human existence, humans have been intermittently calorie limited. We ate a lot when we had access to food and starved when we did not. Our ability to convert excess calories to fat (the preferred stored energy of animals) was key to our survival as individuals and a species. It is only a slight exaggeration to say that everyone alive today is alive because our ancestors could get fat. Today, almost no people *in affluent society* experience periods of involuntary starvation; we generally have an abundance of calories available. The ratio of nutrients to calories is called “nutrient density.” Skim milk is considered nutrient dense because it contains a large amount of protein, calcium, magnesium, potassium, etc. per calorie consumed. Humans are now experiencing caloric over-nutrition while also experiencing selective under-nutrition for certain nutrients. For many people, a more nutrient dense food supply would be highly desirable.

Everything we think of as a nutrient is competing with energy storage or vegetative growth for a limited supply of energy in plants — even in an unconstrained environment like hydroponics in a growth chamber. Calcium, phosphorus, vitamin C, omega-3 fatty acid, and antioxidants are all jostling to capture a part of the energy flow with demand for these components influenced by the overall health of the plant. One possible explanation for a decline in food nutrient density is the plants are more productive (healthier) and are diluting nutrients with additional energy storage molecules (oils, carbohydrates) because this is the *optimal situation for the plants*.

It bears repeating that plants are the foundation of the entire biosphere. *Everything else wants to eat them.* From the beginning, plants needed to defend themselves from parasites and predators (like us). Some defenses are physical; the husk of a seed is hard and fibrous. This makes it harder for an insect to chew through. Fibrous, tough leaves and bark discourage grazing animals. In most cases, these physical defenses are poorly digestible so attempting to digest them uses up the parasites’ energy for less gain. Plants also acquired chemical defenses — with phenolics having a major role. Many phenolics bind to proteins and inhibit their functionality. When the functionality is digestion, the parasite attempting to eat the plant loses the benefit of the meal they just ate. For example, wheat seeds have a high fiber seed coat that also contains a variety of phenolic compounds, some of which are insecticidal (and also this) or fungicidal. Seeds that fall on the ground are prepared to resist potential consumers until they germinate (when other defenses develop).

Evolution leads to some funny outcomes. Our gut microbiome developed with a dependence on those indigestible fibers as a food source and we developed a dependence on a healthy gut microbiome. Those phenolics that inhibit digestion become our antioxidants and anti-inflammatory compounds. Some of those protease inhibitors have potential as anti-carcinogenic agents. Which brings us back to soil health again. Stress in the soil induces greater accumulation of phenolics in plant tissues. It is possible that practices that promote healthier soils and thus healthier crops also decrease the need for the plant to mount robust defenses. So, we have increasingly grown crops with lower concentrations of wellness-inducing compounds because of generally improved plant health. Increased use of fungicides and insecticides would also contribute to stress reduction and decreased secondary metabolism. And secondary metabolism diverts the plant's energy and materials away from growth and reproduction itself.



FAO data

If climate change increases stress on plants, we may see rising concentrations of these quasi-nutrients again, but at a cost. Famine is still with us. In 2019, about 150,000,000 people suffered from protein-energy malnutrition and 185,000–245,000 people died worldwide. The map below illustrates the overall soil health with some of the poorest countries having the least healthy soils.

Nowhere is healthy soil more important than in regions where soil and economic poverty overlap with climate vulnerability. And nowhere is it more clear that we must be careful to not let the great be the enemy of the good.