Nurturing diversity in our guts and on our farms to reduce health risks and increase food system resilience

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KEY MESSAGES:

- → **Crop diversity increases resilience of farm production to climate changes and damage from pests and diseases.**
- → **Science has associated biodiversity with human physical and mental health linked to the composition and diversity of the microbiota in our intestines.**
- → **Dietary diversity is of paramount importance for having a healthy microbiota.**
- → **A diverse diet needs diversity in production systems. So we need to rethink plant breeding from 'cultivating uniformity' to 'cultivating diversity'.**
- → **One way to cultivate diversity quickly and inexpensively is by using a method called evolutionary plant breeding.**

Introduction: seed at the heart of global challenges

Climate change, poverty, hunger and malnutrition, water, biodiversity in general and agrobiodiversity in particular are issues that have featured strongly in a number of recent reports and reviews (1–4). These issues are often covered separately even though they are closely interconnected with each other. One major interconnection is seed.

Seed is related to climate change because we need crops better suited to the climate as it changes. Seed is associated with food as most of our food comes directly or indirectly from plants. Through food and child nutrition, seed is linked to poverty (5). Seed is related to water, because about 70% of fresh water is used in agriculture (6), so varieties producing a yield with less water will make more water available for human uses. Seed is associated with malnutrition: the three crops from which we derive about 60% of our plant-based calories and 56% of our plant-based proteins – namely maize, wheat and rice (7, 8) – are far less nutritious than barley (9) or millets and sorghum (10, 11). Millets and sorghum are not only more nutritious, they also need less water than maize, rice and wheat, which use nearly 50% of all the water used for irrigation.

Finally, seed is related to biodiversity in general and to agrobiodiversity in particular. Agrobiodiversity is important for food security (12), for increasing farm income and generating employment, and for reducing exposure to risk (13, 14).

Maintaining or increasing agrobiodiversity reverses the tendency of modern plant breeding towards uniformity (15). The main cause for the dramatic reduction of genetic diversity is breeders selecting predominantly for varieties to be usable under the widest possible conditions. This decline in diversity has increased the vulnerability of crops (16–19) because their genetic uniformity makes them unable to respond to climate changes, especially short-term changes. In addition, uniform crops provide an ideal breeding ground for the rapid emergence of fungicide-resistant variants (19) as shown by the potato late blight epidemic and ensuing famine in 19th century Ireland (20). Crop diversity, by contrast, has been shown to be highly beneficial in restricting the development of diseases (21–24). For example in China, the use of variety mixtures of rice led to a reduction of rice blast of 94% and increase in yields of 89% compared to monocultures. Farmers were able to cease use of fungicidal treatment of crops within two years. One of the most notable examples of the advantages of mixtures was the expansion of barley mixtures in the former German Democratic Republic during the years 1984–1991. Expanding the barley mixtures to 360,000ha led to a reduction of the percentage of fields affected by severe mildew epidemics from 50% to 10% and a threefold reduction of the percentage of fields sprayed with fungicides (25).

The biodiversity inside us

Science has associated the decrease of biodiversity with the increase of certain diseases in humans, ranging from inflammatory bowel disease, to ulcerative colitis, cardiovascular disorders, various liver diseases and many types of cancer (26). In turn, the increase in the frequency of inflammatory diseases has been associated with a decreased efficiency of our immune defences (26). Recently, the association has been confirmed between the microbiota – namely the complex of bacteria, viruses, fungi, yeasts and protozoa that is in our intestine[i] – and our immune system and with the likelihood of contracting inflammatory diseases (27).

The average human microbiota weighs around 2kg (about 0.5kg more than the average human brain) and plays a number of important functions, from the synthesis of vitamins and essential amino acids, to the breakdown of what has not been digested in the upper intestinal tract. Some of the products of these activities represent an important energy source for intestinal wall cells and contribute to intestinal immunity.

Some of the most recent research (28) has shown that in melanoma patients who were capable of responding to immune therapy, the microbiotas had a different composition and were more diverse than those of patients who did not respond well. The research concluded that both the composition and the diversity of the microbiota are important in determining anti-tumour immunity. The response of laboratory mice that received a faecal transplant from human patients who had responded to the therapy supported the results. Faecal transplantation involves transferring the microbiota from a healthy patient to a patient with a disease and is becoming a widespread practice for the treatment of diseases that do not respond to antibiotics (28).

The microbiota also appears to be involved in several neuropsychiatric disorders such as depression, schizophrenia, autism, anxiety and stress response (29). This is likely due to the damage that inflammatory processes cause to myelin, the sheath surrounding the neurons, thus altering the normal transmission of nerve impulses.

Diet, human health and environmental health

Diet strongly influences the microbiota: a change in diet alters its composition in just 24 hours. It takes 48 hours, after changing the diet back again, before the microbiota returns to its initial conditions (30).

Given the important roles of the microbiota on the one hand, and the fact it is so strongly and rapidly influenced by diet on the other, it is understandable that there have been many studies on the effect of various diets (Western, omnivorous, Mediterranean, vegetarian, vegan, etc.) (30). Recent results demonstrate that the composition and diversity of gut microbiota are not significantly associated with genetic ancestry, but shaped predominantly by environmental factors (diet and lifestyle) (31). Diet diversity is of paramount importance for having a healthy microbiota (32).

The diet also links environmental and human health. Rising incomes and urbanization are among factors driving a global dietary transition in which traditional diets are replaced by diets higher in refined sugars, refined fats, oils and meats (33). By 2050 these dietary trends, if unchecked, will be a major contributor to global land clearing and to an estimated 80% increase in global agricultural greenhouse gas emissions from food production (33). Moreover, these dietary shifts are greatly increasing the incidence of type 2 diabetes, coronary heart disease and other chronic non-communicable diseases that lower global life expectancies (33). Diet is now the number-one risk factor for the global burden of disease (34).

A study conducted in Zambia showed that household dietary diversity is positively associated with production diversity, and in turn, production diversity is positively associated with indicators of nutritional status of children aged two to four (35). This effect has been confirmed by some studies (36) but not by others (37) partly because of difficulties associating indicators of agricultural diversity with indicators of nutritional status (38).

Diversity and uniformity

So, human health needs a diverse microbiota, a diverse microbiota needs a diverse diet, and a diverse diet needs diversity in production systems. However, global trends and policies do not work in favour of diversity. How can we have a healthily diversified diet if, as mentioned earlier, 60% of our calories come from just three crops, namely wheat, rice and maize (7)? And how do we diversify our food if almost all the food we eat is produced from crop varieties that, to be legally marketed, must be registered as uniform (Box 1)? How can we have a diversified diet if the agriculture that produces our food is based on uniformity?

BOX 1 – Registry of plant varieties

In most countries today, plant varieties need to be registered before they can be released in markets.

Registry of plant varieties was introduced in Europe in the mid-19th century to protect consumers by guaranteeing that purchased seed would be:

- **Distinct** from other varieties
- **Uniform** in its essential characteristics
- **Stable** so that it would not change when multiplied.

The characteristics that are promoted in this system are the opposite of those needed in a sustainable food system. Adaptability not stability is needed in order to adapt to new and changing climate conditions. Variability not uniformity supports yield stability when conditions are unfavourable and changeable.

Between the need to diversify our diet and the uniformity imposed by law on seed and thus on crops there is an obvious contradiction. In addition, there is a further contradiction between uniformity and stability on the one hand and the need to adapt crops to climate change on the other.

Cultivating diversity

Most food derives from seeds. Therefore, a primary solution to the health problems afflicting the world today can be sought in the way that seeds are produced. Since seeds are produced by plant breeding, to change things we have to rethink how plant breeding is conducted in order to move from 'cultivating uniformity' to 'cultivating diversity'.

Today, much institutional plant breeding (both private and public sector) has industrial agriculture as its objective. Institutional plant breeding aims to 'cultivate uniformity', complying with the seed laws mentioned earlier, and producing uniform varieties bred to maximize crop yields with the support of fertilizers and pesticides. Once considered the only option to feed the world, the effectiveness of this model of agriculture is being questioned by recent research as being neither resilient nor sustainable (39). The human cost of the current food system is that almost 1 billion people are hungry and almost 2 billion people are eating too much of the wrong food (39, 40) which is artificially cheap (41). Evidence suggests that more than 80% of the world's food in value terms is produced on family farms (42).

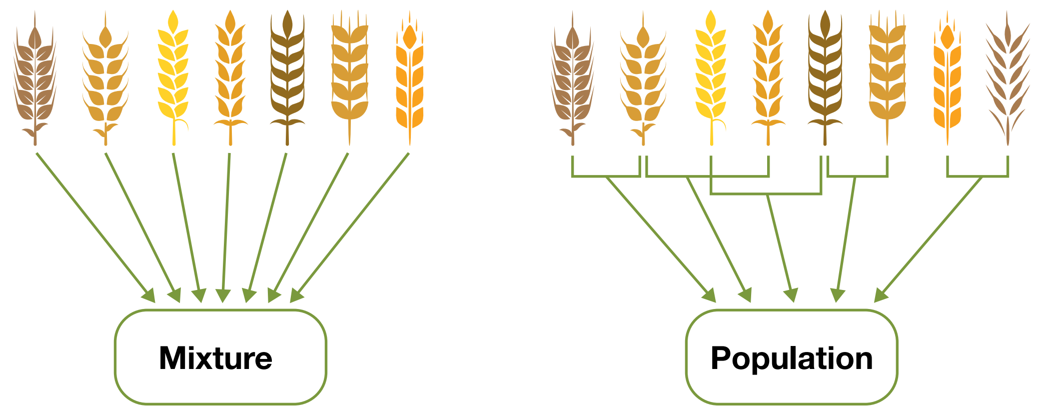
One way of 'cultivating diversity' quickly and inexpensively is by using a method called evolutionary plant breeding (43, 44) (Box 2). Evolutionary plant breeding consists of cultivating mixtures or populations (Figure 1).

The starting point of evolutionary plant breeding could be a mixture of seeds, obtained by mixing an equal quantity of seed of a number of varieties of the crop in question (Figure 1, left). Alternatively, it could be an evolutionary population made by crossing a number of varieties (Figure 1, right). The ideal evolutionary population would be made up of all possible combinations of varieties. In either case, the choice of how many or which varieties depends on the farmer's objectives. For example, if disease resistance is one of the problems affecting productivity in the target environments, one or more parents of the evolutionary population or one or more varieties in the mixture should carry the desirable genes of disease resistance. The increasing availability of genetic markers associated with desirable genes is making the handling of evolutionary populations ever easier.

Once a mixture or a population is planted, it is left to evolve as a crop. In other words, it is planted and harvested, using part of the harvest as seed for the next season, or to select the best plants, or both. Thanks to the natural crossings that occur between plants, what was originally a mixture also becomes a population. The only difference is that in this case, we have no control over the crossing and therefore we do not know how the different parents contributed to the population.

Through the joint effects of natural selection and natural crossing, the seed which is harvested is genetically different from the seed that was planted. In other words, the populations (including those derived from an original mixture) evolve continuously. This is why they are called 'evolutionary'. The farmers therefore have the opportunity to adapt the crops to their soil, their climate and to the particular way in which each of them practises agriculture, including organic farming.

FIGURE 1 – The difference between mixtures and populations: a mixture is obtained by mixing seed of different varieties while a population is obtained by crossing different varieties



BOX 2 – Evolutionary plant breeding: a history

The science of evolutionary plant breeding goes back to 1929. Harlan and Martini proposed the composite cross method of plant breeding and synthesized a barley composite cross (known as CC II) by pooling an equal number of F_2 seeds[ii] obtained by 378 crosses between 28 superior barley cultivars representing all the major barley growing areas of the world (45). Composite crosses and mixtures have shown that they are able to evolve towards a higher yield, higher yield stability over time, and a higher level of disease resistance during subsequent generations (43, 46–51).

Evolutionary populations adapt to different geographical areas by ripening earlier in warm locations and later in cold locations (52). They tend to perform better than uniform varieties in years affected by drought (53) and they can combine higher yield and higher yield stability (54–56). A meta-analysis of 91 studies and more than 3,600 observations concluded that cultivar mixtures are a viable strategy to increase yield, yield stability and disease resistance (57).

In a project which introduced evolutionary populations in Iran[iii] customers reported that the bread made from an evolutionary population of bread wheat was beneficial to health (58). Experiences in Italy found that an evolutionary population of over 2,000 different types of bread wheat from all over the world brings forth a bread that, besides having an extraordinary smell and taste, is tolerated by people suffering from gluten intolerance. This population has been dubbed the 'Aleppo mixture' in recognition of its provenance from Syria. In Iran, shepherds who have used an evolutionary barley population to feed sheep have noted an improvement in milk quality. Recently, pasta produced from a population of durum wheat by three different producers in Italy was unanimously considered by different informal panels of consumers of superior taste to what is considered the best quality pasta.

The rapid adoption of these evolutionary populations, and the reports on the benefits of their products, which are receiving constant confirmation, indicate that the cultivation of evolutionary populations, represents a dynamic way of cultivating crops.

Conclusions

Seed connects climate change, poverty, malnutrition, water and biodiversity – both wild and agricultural. Even the diversity in our guts, fundamental to good physical and mental health, relies on diversity in diets, which in turn relies on diversity in agriculture. This means cultivating diversity rather than cultivating uniformity, the opposite to current industrial agricultural models.

Evolutionary breeding is one way to confer resilience and adaptability through cultivating diversity. The evolutionary populations adapt to local conditions, resist disease and have sensory qualities that consumers appreciate. Very few inputs are needed, which contributes to increasing farmers' independence from an industrialized and financialized agricultural model. Evolutionary breeding increases genetic diversity within crops. For healthy environments, healthy diets and healthy microbiota, diversity is needed across the landscape, with a variety of species, functional types, and land uses fostering resilience and health. Increased diversity in the field will support food and diet diversity, which through gut diversity and composition are key to human health and nutrition.

Notes

[i] Sometimes called the microbiome, which actually refers to the genes of the microbiota.

[ii] In plant breeding every cross is assigned an F (filial) number: F1 is the first generation cross (i.e. between the first two original parents). An F_2 is the second generation after a cross.

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