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Displacing Empty Calories with Nutrient Dense Food:

How can UK farmers be rewarded for practices that promote nutrient density?

Written by:

Dr Hannah Fraser NSch

April 2025

A NUFFIELD FARMING SCHOLARSHIPS REPORT

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A NUFFIELD FARMING SCHOLARSHIPS REPORT (UK)

NUFFIELD Farming Scholarships

"Leading positive change in agriculture. Inspiring passion and potential in people."

Date of report: April 2025

Title	Displacing empty calories with nutrient dense food: How can UK farmers be rewarded for practices that promote nutrient density?
Scholar	Dr Hannah Fraser
Sponsor	The Yorkshire Agricultural Society & The Worshipful Company of Fruiters
Objectives of Study Tour	1. To understand, what is nutrient density? 2. How do farming practices alter the nutrient density of foods 3. How can farmers be financially rewarded for providing greater nutrient-density
Countries Visited	USA, Canada, Italy, The Netherlands, Denmark, France Global Focus Programme: Texas, Germany, Ireland, Northern Ireland
Findings	A growing number of researchers and farmers are exploring how farming methods affect the nutrient quality of food. Through my study tour, I identified four key areas where evidence demonstrates a clear link between farming method and nutrient density: 1. **Soil Health**: Regenerative farming practices that improve soil health can increase the populations of beneficial microorganisms, which play a crucial role in nutrient cycling. Healthier soils could therefore lead to more nutrient-rich crops. 2. **Breeding and Variety Selection**: Selecting and breeding crop varieties with a greater ability to take up nutrients could help to improve nutrient density. 3. **Biofortification**: Enhancing the nutrient content of crops either through selective breeding to take up a particular nutrient, or by applying nutrients directly to plants during growth, potentially leading to foods that are richer in minerals. 4. **Animal Feed**: Influencing the nutritional content of animal products: meat, milk and eggs, through optimising the animals' diet. While the benefits of these methods are promising, there is still much work to be done. Collaboration between researchers and farmers is essential to gain further understanding about the impact of different farming practices on food quality. Large-scale human health trials may also be needed to confirm the health benefits of consuming more nutrient dense foods. Additionally, healthcare professionals must become more aware of how food quality, influenced by farming methods, can affect health.

EXECUTIVE SUMMARY

The UK faces a growing health crisis, with rising rates of chronic diseases putting immense pressure both on individuals and the NHS. While the link between food and health is now well-established, emerging evidence suggests that the **way** food is produced could also play a critical role in combating our health issues. Farmers could be key to improving public health by enhancing the nutritional quality of their produce.

The idea that "food is medicine" dates back to Hippocrates, but modern research is revisiting this concept with a new focus: not just on **what** we eat, but **how** our food is produced. Concerns are mounting that the nutrient density of our food is in decline. This has sparked interest in whether changes in agricultural methods could lead to more nutritious food, thereby helping to prevent chronic diseases and promote good health.

A small but growing number of researchers and farmers are exploring how specific farming methods could boost the nutritional content of food. If successful, these methods could be integrated into broader strategies to improve public health. Through my study tour, I identified four key areas where evidence demonstrates a clear link between farming method and nutrient density:

1. **Soil Health**: Regenerative farming practices that improve soil health can increase the populations of beneficial microorganisms, which play a crucial role in nutrient cycling. Healthier soils could therefore lead to more nutrient-rich crops.
2. **Breeding and Variety Selection**: Selecting and breeding crop varieties with a greater ability to take up nutrients could help to improve nutrient density.
3. **Biofortification**: Enhancing the nutrient content of crops either through selective breeding to take up a particular nutrient, or by applying nutrients directly to plants during growth, potentially leading to foods that are richer in minerals.
4. **Animal Feed**: Influencing the nutritional content of animal products; meat, milk and eggs, through optimising the animal's diet.

While the potential benefits of these methods are promising, there is still much work to be done. Collaboration between researchers and farmers is essential to understand the impact of different farming practices on food quality. Large-scale human health trials may also be needed to confirm the health benefits of consuming more nutrient dense foods. Additionally, healthcare professionals must become more aware of how food quality, influenced by farming methods, can affect health.

For real change to occur, comprehensive data collection and stronger evidence are necessary, along with closer collaboration between agricultural and public health

sectors. Farmers who sell directly to consumers have an opportunity to promote the nutritional benefits of their practices, however broader adoption will require systemic changes, including potential new incentives that reward farmers for not just the quantity, but the quality of food they produce. If these efforts are successful, they could lead to a new understanding of the role of food production in public health and potentially reduce the burden of chronic diseases. It could also transform how we value food in society.

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CONTACT DETAILS

Scholar Name: Hannah Fraser

City, County: Cawthorne, Barnsley, Yorkshire

Email: hannah@fraserfarms.co.uk

Website: www.cultivatinghealth.co.uk

Nuffield Farming Scholars are available to speak to NFU Branches, agricultural discussion groups and similar organisations.

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CHAPTER 1: INTRODUCTION

I feel very lucky to have worked in both the medical profession and the agricultural sector. Seeing the intersection between these two critical sectors has been a source of inspiration and something that motivated me to apply for a Nuffield Farming Scholarship. I studied medicine at The University of Edinburgh, graduating in 2020 at the start of the Covid-19 pandemic. I began working in Leeds across a range of specialties including paediatrics, elderly medicine, surgery and general practice. I now work as a junior doctor in Leeds Children's Hospital. I believe it is a privilege to work in healthcare. However, it is frustrating when you are unable to resolve the chronic diseases that so many people live with. I am increasingly interested in how our lifestyle, including how we eat, sleep, exercise and live, impacts our risk and burden of disease.

In 2018 my husband and I had the opportunity to take over the management of a farm. Neither of us had experience of farming; we had little knowledge of food production systems. With our increasing interest in the role of food and diets in health, we jumped at the opportunity. We knew we wanted to produce nutritious food that could serve our local community, whilst working with nature.

We transitioned the land to organic production and now grow organic milling cereals that we sell to local mills. We have a keen focus on improving soil health and biodiversity, and we experiment with bi-cropping, multi-species winter covers, minimum tillage and agroforestry. Our journey into regenerative farming was driven by an acute awareness of the environmental pressures our modern society faces. Over the past few years, I have come to realise that the tools we have as farmers to improve environmental health could also prove critical for improving human health.

I believe it is our food, and fundamentally our food producers, who could offer a solution to the rapidly rising levels of chronic disease. As Lady Eve Balfour put simply, **"the health of the soil, plant, animal and man is one and indivisible"**.

I was thrilled to have been awarded a 2023 UK Nuffield Farming Scholarship to investigate the role farming plays in the nutrient value of our foods, and how this could affect human health. I hope by sharing the information that I have learnt on this journey, I will help to draw attention to the importance of not just **what** we eat, but **how** we grow the food that we eat.

CHAPTER 2: MY STUDY TOUR

A huge thank you goes to the Nuffield Farming Scholarships Trust, and to my sponsors, The Yorkshire Agricultural Society and The Worshipful Company of Fruiterers, for gifting me the opportunity of my Nuffield travels.

My journey started in November 2022 at the Nuffield annual conference, held in Cardiff. I met my fellow 2023 scholars, a wonderful group of people from a range of backgrounds, all investigating a diverse array of topics, from farming seaweed and insects, to agricultural journalism and renewable energy.

In March 2023, the scholar year group convened in London to begin an exciting two weeks of training. Our week in London involved meeting a variety of people from the agricultural industry and discussing policy, lobbying, farming innovations and business development. We then flew to Vancouver, where we met our international year group: over 100 scholars from 15 different countries. We discussed the issues that the agricultural industry faces, and the successes and innovations that are taking place globally. We learnt about how agriculture differs across the globe, including the different policy issues, funding systems, climate conditions, culture and public attitudes.

My first independent travel led me on an eight week road trip around the USA, where I had the pleasure of meeting many inspiring researchers, farmers and food industry experts. With knowledge gained from that trip, I later sought out visits across Europe, including in the Netherlands, Denmark and France. I attended the Micronutrient Forum Conference in Rotterdam and the European Public Health Conference. I had the opportunity to join as a youth delegate at the FAO's Sustainable Livestock Transformation meeting, held in Rome. I also had the pleasure of meeting several researchers in the UK, including Rothamsted and Newcastle University.

I was incredibly lucky to receive sponsorship to join the Global Focus Programme, where I travelled to Texas, Germany, Ireland and Northern Ireland. This three week adventure was an incredible opportunity to witness the breadth of farming systems that exist in these countries. I toured alongside fellow Nuffield Scholars from Australia, New Zealand, Brazil, Poland, Ireland and the USA. The chance to hear their experiences and ideas was a hugely valuable part of the GFP.

CHAPTER 3: FARMING, FOOD AND HEALTH: WHAT'S THE LINK?

As a doctor, I am increasingly concerned by the rising tide of chronic diseases. Type 2 diabetes, high blood pressure, arthritis, dementia, irritable bowel syndrome, diverticulosis – these are just some of the chronic conditions that are becoming increasingly common. While modern medicine has made remarkable advancements in treating certain conditions and extending our life expectancy, the burden of chronic disease remains high and ultimately threatens our quality of life. We have an abundance of pharmaceuticals at our disposal, yet they are often ineffective in curing these chronic conditions. Too often, it feels like we lack real solutions. So what then?

There is growing recognition of the role that food plays in health. For some this is not a new concept. Hippocrates, a Greek physician, famously said in 440BC, **"Let food be thy medicine"**. Today much discussion centres around what we should eat to promote health. Reducing ultra processed foods and eating a diversity of whole foods I am sure can radically improve one's health. But is that enough, or do we need to go further as we search for ways to optimise our health, thinking not just about **what we eat** but also about **how our food is grown**?

When I started farming seven years ago, I realized how little I truly understood about food production. Farming is not a one-size-fits-all endeavour. Each farmer must navigate their unique combination of land, soil and climate. Every year, a farmer makes countless decisions that influence not only yields but also, ultimately, the nutritional quality of the food they produce.

For previous generations, the primary goal of agriculture was to produce enough calories to prevent starvation – a crucial challenge that farmers met with remarkable success. Thanks to technological advancements, improved genetics and chemical inputs, crop yields have soared. Since the 1960s, global wheat production has tripled, providing a stable source of calories for many.[1] Today, as a globe, we produce around **2,800 kcal of food per person per day**,[2] more than enough to meet global calorific needs. But is it enough to simply grow sufficient calories?

A growing concern is whether we are producing enough **nutrient-dense** food. Do we, as a global population, access sufficient **vitamins and minerals** through our diet – essential for countless physiological functions – to achieve optimal health? Take iron deficiency anaemia, for example. Insufficient iron intake can lead to symptoms like chronic fatigue and breathlessness. What about phytochemicals, the plant compounds with powerful health benefits, including cancer-fighting properties? Although there are no official dietary recommendations for

phytochemicals, consuming fewer of them could have significant consequences for long-term health.

Multiple studies suggest that the micronutrient and phytochemical content of our food is declining. Over the past 100 years, agriculture has undergone significant changes, including the development of new crop varieties, increased use of fertilizers and pesticides, widespread irrigation and the separation of livestock from arable farming. These advancements have undoubtedly increased food production, but as calorie production has increased, has the production of essential nutrients, such as vitamins, minerals and phytochemicals, kept pace? Does the **way we farm affect the nutritional quality of our food**? If so, can farmers adopt methods that **enhance the nutrient density** of their crops, potentially improving human health?

These questions have driven my research over the past two years as I travelled the world as a Nuffield Farming Scholar, meeting and interviewing experts in agriculture, nutrition and health. It has been a fascinating journey, and in the following pages I will share my findings. This report aims to contribute to the growing body of evidence connecting food, farming and health. It is a summary of the key insights I have gathered and highlights areas that warrant further research and innovation.

CHAPTER 4: WHAT IS NUTRIENT DENSITY?

One of the first questions I asked in my research was: **What is Nutrient Density?** The answer is not as straightforward as one might hope – there is no universal consensus on its definition. Food is far more complex than just macronutrients like starch and protein. It contains a vast array of compounds that interact in ways we are only beginning to understand.

At its core, nutrient density refers to the concentration of essential nutrients in a given food. There are three main categories of nutrients in our food:

- **Macronutrients**: proteins, fats, carbohydrates and fibre, which we require in large amounts.

Image from: https://thebekindpeopleproject.org/blog/2024/08/21/understanding-macronutrients-and-micronutrients

- **Micronutrients**: vitamins and minerals, which are needed in smaller quantities but serve many crucial functions in the body.

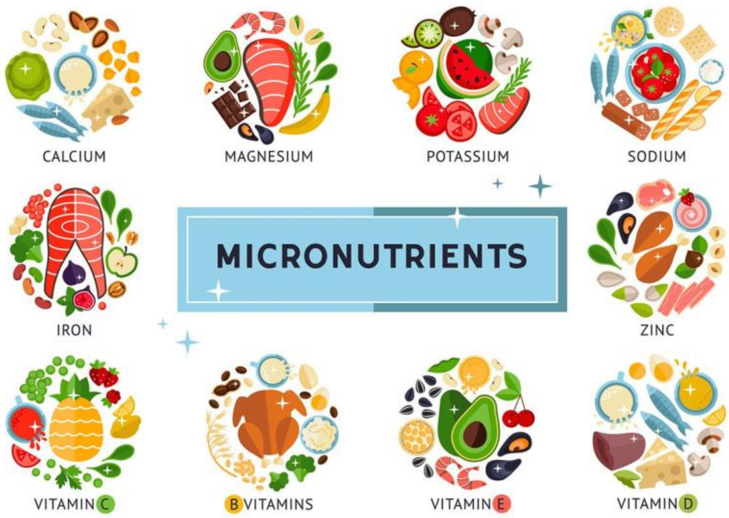
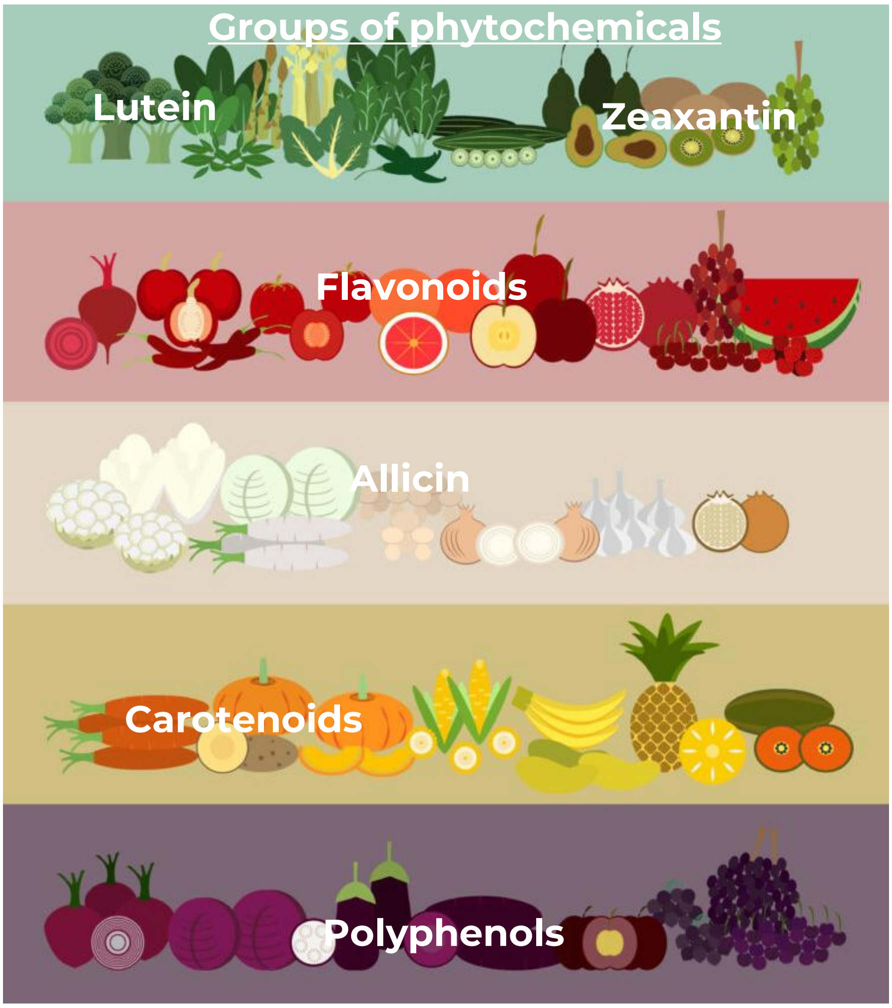


Image from: https://thebekindpeopleproject.org/blog/2024/08/21/understanding-macronutrients-and-micronutrients

- **Phytochemicals**: natural plant compounds, with many important health benefits, including reducing inflammation, improving immune function and fighting cancer cells. Whilst phytochemicals are considered 'non-essential nutrients', meaning there is no minimum intake requirement for survival, they are essential for optimal health.

Many different groups of phytochemicals have been identified, including carotenoids and polyphenols. Yet there are many that are not yet discovered; researchers use the term 'nutrition dark matter' as using mass spectrometry, you can measure tens of thousands of phytochemicals in food, yet we currently only have names for a few hundred.



The amount of nutrients in food, compared to its calorific value, matters for two key reasons:

1. **Efficient Nutrition**. Nutrient-dense foods provide essential nutrients without excessive calories, helping individuals meet their dietary needs while avoiding overconsumption that could contribute to weight gain.
2. **Nutrient Interactions**. Foods contain multiple nutrients that interact with one another, meaning it's not just about how much of a nutrient is present, but also how it is balanced with other compounds in the food matrix.

Given this complexity, various attempts have been made to define and measure key nutrients, allowing a universal 'nutrient density' score to be assigned allowing foods to be compared with one another.

One influential approach comes from Dr. Adam Drewnowski, whose work on nutrient profiling led to the creation of a **nutrient-rich food index**, giving foods a score based on their nutrient-to-calorie ratio.[3] It considers which essential nutrients to encourage, such as protein, fibre, vitamins and minerals, and which nutrients to limit, such as saturated fat, sugar and sodium. However, it does not include reference to phytochemicals, as currently no national guidance exists on the minimum amount of phytochemicals needed for health.

Dan Kittridge from the **Bionutrient Food Association** is an inspirational figure; a farmer who has devoted years trying to understand the nutrient density of foods. The Bionutrient Institute have also attempted to develop a measure of nutrient density, called the **Bionutrient Quality Index (BQI)**, which aggregates measurements of antioxidants, polyphenols, protein, magnesium, sulphur, potassium, calcium, iron and zinc into a single score. This index offers a practical way to compare the nutrient density of crops, though its creators acknowledge its limitations:

"This index value is our starting point for developing a practical and measurable definition for nutrient density in crops. It in no way represents scientific consensus but serves as a useful placeholder. Over time, we hope to engage with food scientists, nutritionists and others to refine it further."

Ultimately, to define nutrient density in a meaningful way, we must agree on which nutrients, and in what balance, we should prioritise in our food. This remains an evolving discussion and one that is critical to both farming and human health.

Evidence of declining nutrient density over time

Several studies have suggested that the foods we eat today are less nutritious than they once were. One of the earliest researchers to investigate this was Dr. Anne Mayer, who analysed historical data from *McCance and Widdowson's Composition of Foods*, a UK government database published every few decades. Comparing the mineral content of 20 fruits and vegetables from the 1930s to the 1980s, she found striking declines in key minerals:

- **48% less calcium in carrots.**
- **60% less magnesium in cabbages.**

Across all 20 fruits and vegetables, significant reductions were observed in calcium, magnesium, copper and sodium in vegetables, and magnesium, iron, copper and potassium in fruits.[4]

Similar findings have been reported in fruits and vegetables in both the United States and Finland:

- **USDA data (1950–1999)**: Significant declines in calcium (-16%), phosphorus (-9%) and iron (-15%).[5]
- **Finnish data (1970–2000)**: Declines in potassium, manganese, zinc, copper and nickel.[6]

More recent comparisons in the UK, using data from 2019, showed that while levels of some minerals such as calcium and magnesium have shown some improvement – I suspect due to the addition of calcium and magnesium lime – others had deteriorated further. Between the 1940s and 2019, **iron levels in fruits and vegetables dropped by 50% and copper by 49%**.[7]

These declines have real health implications. **Iron** is essential for oxygen transport and immune function, and deficiency remains widespread in both industrialized and developing nations. **Copper** is critical for enzyme activity, blood cell formation, glucose metabolism and brain development.

Is this a real trend?

Some scientists have cautioned against overinterpreting historical data, noting that sampling methods were not standardized and that analytical techniques have evolved. However, Elsie Widdowson, a co-author of *The Composition of Foods*, stated that while methods had changed, older techniques were just as accurate – if more time-consuming – than modern automated ones.

While methodological limitations exist, the fact that similar nutrient declines have been observed across three different national datasets suggests this is a genuine trend worth investigating further.

Historical decline in the nutritional quality of wheat

On a visit to Rothamsted Research Centre, I learnt about their **Broadbalk Experiment**, where they have been growing wheat continuously since 1843. They explored nutritional changes by testing archived grain and soil samples.[8] They observed:

- Between the 1850s to the 1960s, grain mineral concentrations remained stable or increased slightly.
- From the 1960s onward, sharp declines were observed in iron, zinc, copper and magnesium concentrations in the grain.

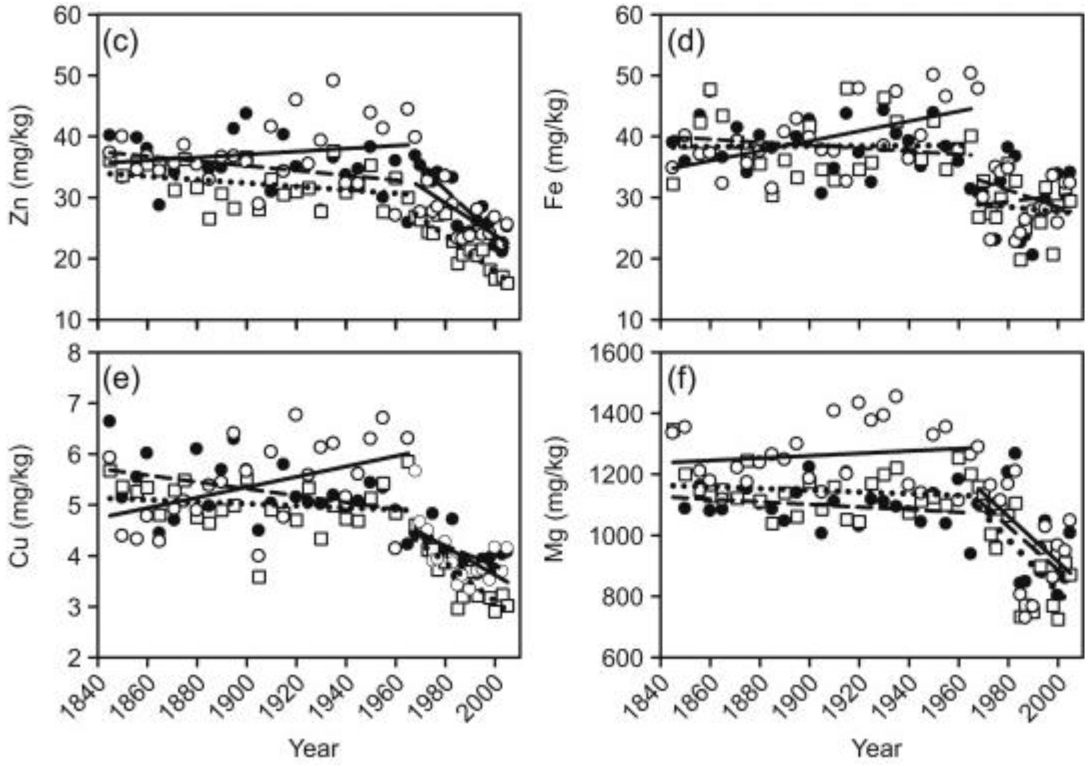


Fig. 1: Trends in wheat grain concentrations of Zinc (c), Iron (d), Copper (e), and Magnesium (f) from three plots of the Broadbalk Experiment since 1845. Regression lines are shown for (c)–(f): dashed line for the control (no fertiliser), dotted line for artificial fertiliser, and solid line for farmyard manure. Image from reference [8].

This timeline coincides with the introduction of **dwarf wheat varieties**. In the **Green Revolution (1960s–70s)**, plant breeders developed high-yielding, disease-resistant wheat varieties that replaced traditional heritage wheats. These new varieties doubled grain yields, helping to prevent famine. However, while these new wheats dramatically increased food production, this data suggests there was an **unintended consequence**: a decrease in mineral concentration.

An additional discovery was made that even in plots where **no fertilizers were applied** and yields averaged only 1 tonne/ha, the nutrient content of these modern dwarf wheat varieties was still lower than that of older varieties. This suggests that the issue is not simply a **dilution effect** derived from increased yields, but that genetic changes in the wheat itself have reduced the crops ability to take up and accumulate minerals.

Importantly, soil analyses showed **no significant depletion of minerals over time**, reinforcing the conclusion that genetic breeding, not soil degradation, is responsible for the observed declines.

Similar results were seen in hard red winter wheat varieties in the US, where **more recently released varieties contained lower concentrations of iron, zinc, copper and selenium**.[9]

This evidence suggests that modern breeding practices, while increasing yields, have unintentionally **compromised the nutrient density of our food**. These declines in nutrient density may have profound implications for public health, particularly for populations relying heavily on staple crops. Addressing this issue requires **re-evaluating breeding priorities**, a topic that will be explored in the next section.

Understanding variability of nutrient density in the food supply

Whilst data regarding historical changes in the nutritional composition of food comes with limitations, an alternative approach is to look at the variability of nutritional quality in our current food system.

Standard national food composition tables report the **average** nutrient content of different foods, for example the average amount of zinc in a carrot. However, there can be **substantial variation in nutrient levels** of a particular food. This issue was raised in the article that examined the nutrient declines in fruits and vegetables from the US. Whilst the authors examined the mean nutrient values reported in the composition tables, they did note the often-substantial reported range, for example the calcium content in certain foods varied between 30% and 40%, and the iron content by 53%.

This means that two people eating the same food could be getting **very different levels of essential nutrients** depending on factors such as where and how the food was grown.

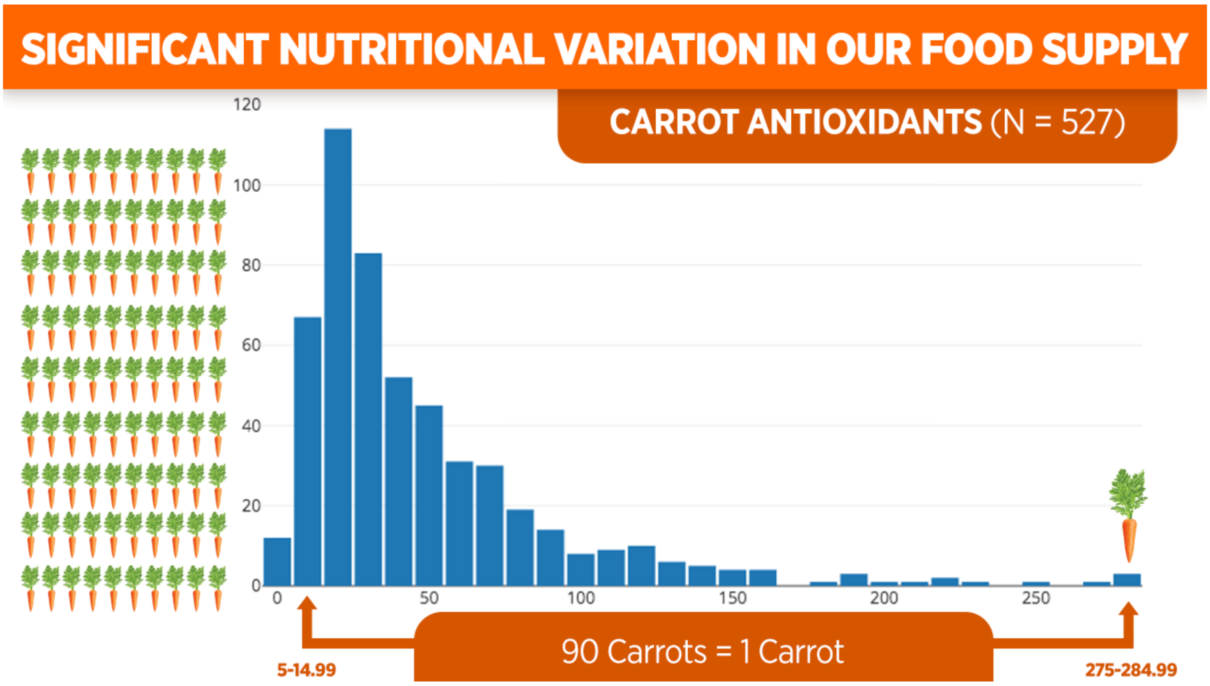
I learnt a great deal from visiting Dan Kittridge of the **Bionutrient Food Association (BFA),** who have been at the forefront of efforts to quantify and understand this variability. Their research aims to:

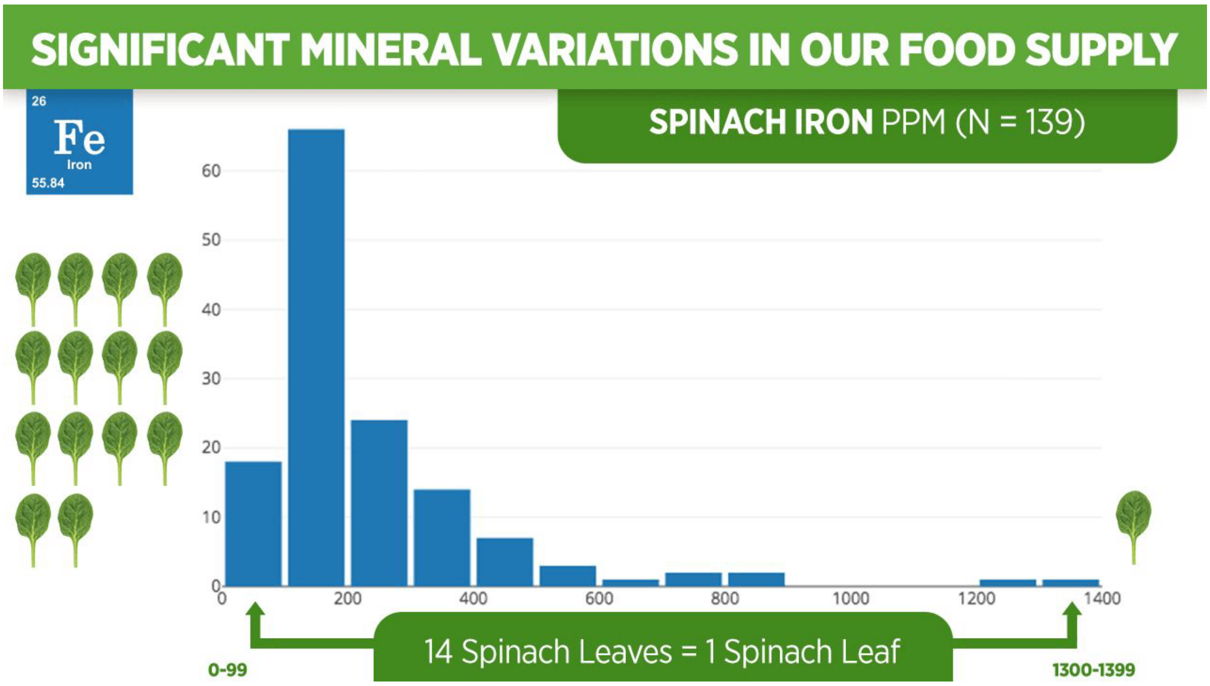
1. Measure the extent of variation in nutrient density within the food supply.
2. Link soil health and farm management practices to nutrient density outcomes.
3. Use spectral data and metadata to predict the nutritional composition of produce.
4. Build a public database of crop nutrition and soil management data to promote better practices.

The BFA has analysed thousands of food samples to better understand nutrient density, revealing striking variations in vitamin and mineral content:[10]

- Calcium levels from samples of kale ranged from only 15%, up to 40% of the adult daily calcium requirement.
- Magnesium levels in spinach ranged from as little as 15% to as much as 35% of the daily magnesium requirement.

- Antioxidant levels in carrots varied dramatically, with some containing up to 90 times more than others.





Images from: The Bionutrient Food Association https://bionutrient.net/site/bionutrient-institute/report-2018

Variability in nutrient density is therefore an established fact, not just a hypothesis. The work of the BFA and other researchers demonstrates that **not all foods are nutritionally equal.** Understanding what drives this variation and how it can be optimized could reshape how we grow, price and consume food, ensuring that the focus moves beyond yield and towards **true food quality.** If nutrient density were **consistent across all food samples**, there would be little reason to study how farming practices influence food quality. However, the large **observed variability** gives motivation to understand how **farming systems play a role in determining nutrient density**.

Why would it matter: Impact of nutrient density on human health

It is estimated that over **two billion people** worldwide experience micronutrient deficiencies. Whilst individuals with poor food access and low diversity diets will be the most vulnerable to micronutrient deficiencies, we must not assume that those living in developed countries with relatively good food access are immune to these issues. Despite advances in food production and distribution, a significant portion of the global population suffers from **hidden hunger**, a form of malnutrition where calorie intake is sufficient, but essential nutrients such as vitamins, minerals, and phytonutrients are lacking.

Even in countries with stable food supplies, micronutrient deficiencies remain widespread. In the UK, for example:

- Amongst **children aged six months to five years**, 31% are estimated to be deficient in iron, and 48% deficient in at least one major micronutrient.[11]
- Amongst **women aged 15-49 years**, 21% are estimated to be deficient in iron, and 43% deficient in at least one major micronutrient.[11]
- **UK dietary surveys** indicate that average intakes of several essential micronutrients, including iron, selenium, iodine, zinc, folate and vitamin D, are **below optimal levels** across the general UK population.[12]

Dr. Linus Pauling, Nobel Laureate, famously stated:

"You can trace every sickness, every disease, and every ailment to a mineral deficiency."

Whilst this is likely an oversimplification, it underscores the fundamental role that micronutrients play in maintaining healthy bodily function, including metabolism, growth, immune function and cognitive function. The vast number of roles that micronutrients play in the body are critical to maintaining health. A significant micronutrient deficiency leads to serious illness and is likely to be diagnosed and addressed. However, it is the **suboptimal levels** of **micronutrients** that often goes undetected but may have significant impact on the risk of developing a chronic disease.

Table 1: Examples of the role micronutrients play in health

Vitamins and Minerals	***Role in maintaining health***
Vitamin A	Key role in the immune system, eyesight and skin health.
Folic acid (Vitamin B9)	Key for the immune system and the production of red blood cells.
Vitamin C	Powerful antioxidant, helping protect cells from damage, helps to produce collagen needed for bones, gums, teeth and skin; key for the immune system.
Iron	Important role in producing red blood cells, brain function and immune health; deficiency leads to anaemia.
Selenium	Needed for skin function and our immune system.
Magnesium	Essential for muscle and nerve function. Low magnesium has been associated with a greater risk of several chronic diseases, including cardiovascular disease, type 2 diabetes, metabolic syndrome, depression and impaired cognition.[13]

Similarly, **phytochemicals** have a whole host of beneficial health effects yet have national recommended minimum dietary intake. The mechanism behind many diseases, including dementia and cancer, is due to the accumulation of **reactive oxygen species** (ROS) that cause **oxidative stress** and **inflammation**. Many phytochemicals act as **antioxidants**, mopping up these ROS and helping to reduce oxidative damage.

There are many different categories of phytochemicals. **Flavonoids,** found in many fruits, vegetables, red wine and cocoa, can improve cardiovascular health and lower blood pressure.[14] Brassica vegetables such as broccoli, cabbage and sprouts, are high in **sulforaphane**, a powerful antioxidant and anti-inflammatory agent. High consumption of sulforaphane has been linked with lower rates of cancer.[15] **Lycopene**, found in red and orange fruits and vegetables, is also a powerful antioxidant and has been found to help reduce cancer risk, particularly for prostate cancer.[16]

CHAPTER 5: CAN FARMING PRACTICES IMPROVE NUTRIENT DENSITY?

The work of the Bionutrient Food Association and others who have demonstrated the variability in the nutritional quality of food is significant. Understanding the underlying causes of this variation is crucial if we are to develop farming practices that consistently improve nutritional quality. While some factors, such as weather patterns, atmospheric CO_2 levels and inherent soil type, are beyond a farmer's control, others – such as crop variety and management practices – can be modified. Over the course of my Nuffield study, I identified **four key areas** where research has shown strong links between farming practices and improved nutrient density:

1. **Soil Health**
2. **Genetics**
3. **Biofortification**
4. **Animal Feed**

Below is a deep dive into each of these areas.

5.1 SOIL HEALTH: UNLOCKING MORE NUTRIENTS FOR PLANTS

Plants rely on soil to provide essential minerals, but not all soils are equally rich in nutrients, nor are all minerals in the soil readily available to crops. Key factors influencing nutrient uptake include:

- **Soil mineral composition**. Some soils are naturally richer in minerals like zinc, selenium and magnesium, while others are deficient.
- **Soil microbiology**. Beneficial microbes play a crucial role in nutrient cycling, breaking down organic matter and making minerals more bioavailable to plants.[17]
- **Soil pH and structure**. Acidic, compacted, or degraded soils can limit nutrient absorption, even when minerals are present. Soil organic matter is the foundation of nutrient cycling and microbial activity. Over the past 50 years, UK arable soils have lost between 40% and 60% of their organic matter due to intensive tillage and synthetic fertilizers.[18]

The role of the farming system

Despite efforts to correlate broad farming labels (such as organic, regenerative, no-till) with higher nutrient density, no clear evidence has emerged. However, one promising finding from the Bionutrient Food Association's analysis of soil samples is a correlation between **greater nutrient density** and **higher soil CO_2 burst test**

results – a measure of microbial activity and soil respiration. This suggests that soil health plays a pivotal role in determining the nutrient content of crops.

A healthy soil ecosystem is **teeming with microbial life** that works symbiotically with plants, much like how the gut microbiome aids human digestion. This concept became clearer to me after meeting researchers **David Montgomery and Anne Biklé** in Seattle, US, who have spent decades studying how farm practices impact soil health and plant nutrition. They describe how many of the essential nutrients in soil are **locked within rock structures** and therefore inaccessible to plant roots. In biologically active soils, however, a diverse microbial community helps release these nutrients, making them available for plant uptake. Their hypothesis is simple yet profound: **the more diverse and abundant the soil microbiome, the more nutrient-dense the crop**. This mirrors the gut microbiome, where a richer diversity of microbes improves nutrient absorption and overall health.

David and Anne's small but well-designed pilot study in the USA tested this hypothesis by comparing crops grown on 10 regenerative farms with those grown on neighbouring conventional farms.[19] The study controlled for climate, soil type and crop genetics by selecting farms in close proximity and ensuring the same crop varieties were used. While the sample size was small, early results suggest that regenerative farms – where soils had greater organic matter – produced more nutrient-dense food. For example, cabbage grown on the regenerative farm had **20% more vitamin C, 41% more vitamin K and 70% more vitamin E**, as well as significantly **more beneficial phytochemicals**. This study design offers a framework for larger trials that could provide more definitive evidence linking soil health to food quality.

Another important research effort is taking place at the **Rodale Institute**, a group of research farms across the USA, committed to advancing organic and regenerative agriculture through research, education and outreach. They have been running the Farming Systems Trial since 1981, comparing organic and conventional arable crops side by side. Their Vegetable Systems Trial now seeks to understand how different practices such as tillage intensity and organic inputs affect soil health and the nutrient density of vegetables.

One particularly fascinating area of research at Rodale is their work on **ergothioneine**, a powerful antioxidant produced exclusively by soil-dwelling fungi and bacteria. Like all antioxidants, it can play a vital role in promoting our health, by mopping up any oxidative damage and helping to reduce inflammation. Within their trial, they grew asparagus, black beans, wheat and oats, all inoculated with a variety of single and mixed species of arbuscular mycorrhizal fungi. They found that the more the plant roots were **colonized with the mycorrhizal fungi**, the **greater the ergothioneine** level in the plant.[20] No-till and low-till systems, which support greater fungal populations, were shown in a separate study to enhance ergothioneine levels in corn, soybeans, and oats.[21]

A large Swedish study demonstrated the profound health consequence of greater ergothioneine in our food. They found that **higher blood concentrations of ergothioneine were linked to lower risks of heart disease and overall mortality**.[22] These findings suggest that farming methods promoting healthy soil microbial communities can directly influence the antioxidant content of our food, with potential long-term health benefits.

The soil-gut microbiome connection

While most research on nutrient density focuses on vitamins and minerals, another emerging area is the relationship between **soil microbiomes and human gut health**. This became particularly clear when I met **Marco van Es,** in the Netherlands, founder of **Bac2Nature**, an organisation exploring how exposure to microbial diversity influences human health. He is working on the research project Soils2Guts along with the University of Leiden, which over the next few years will explore how agricultural practices impact the soil microbiome, crop nutrition and human health.

Research shows that fresh produce contains **live microbes** not just on the surface, but deep within plant tissue. For example, **a single serving of rocket lettuce can contain up to 60 different beneficial bacterial strains**. Using a simulated model, it was shown that microbes present in rocket leaves could survive the digestion process, emphasising that raw plant foods can be an important source of beneficial probiotics.[23] In fact, there is a strong overlap between **bacteria found in fruits and vegetables and those found within a healthy human gut**.[24] Consuming a large diversity of plant foods can help to boost gut health, but perhaps we must also consider how we can farm in ways to boost the microbial richness growing upon, and within raw plant foods.

A growing body of research is starting to explore how farming impacts the microbial richness of food:

- **Rocket lettuce grown in vertical farms** contains far **fewer beneficial microbes** than soil-grown lettuce.[23]
- **Organic farming methods** can increase soil microbial diversity, likely due to manure applications and the absence of synthetic inputs.[25]
- **Homegrown apples and blueberries** have a richer microbiome than commercially grown ones, possibly due to differences in soil health and breeding practices.[26]
- **Apples grown in organic orchards** have a significantly more diverse microbial community compared to conventionally grown apples, particularly in the fruit pulp.[27] In the pie charts below, each colour represents different taxa of bacteria; for the organic apples you can see how

many more colours are present, representing the greater diversity of microbes.

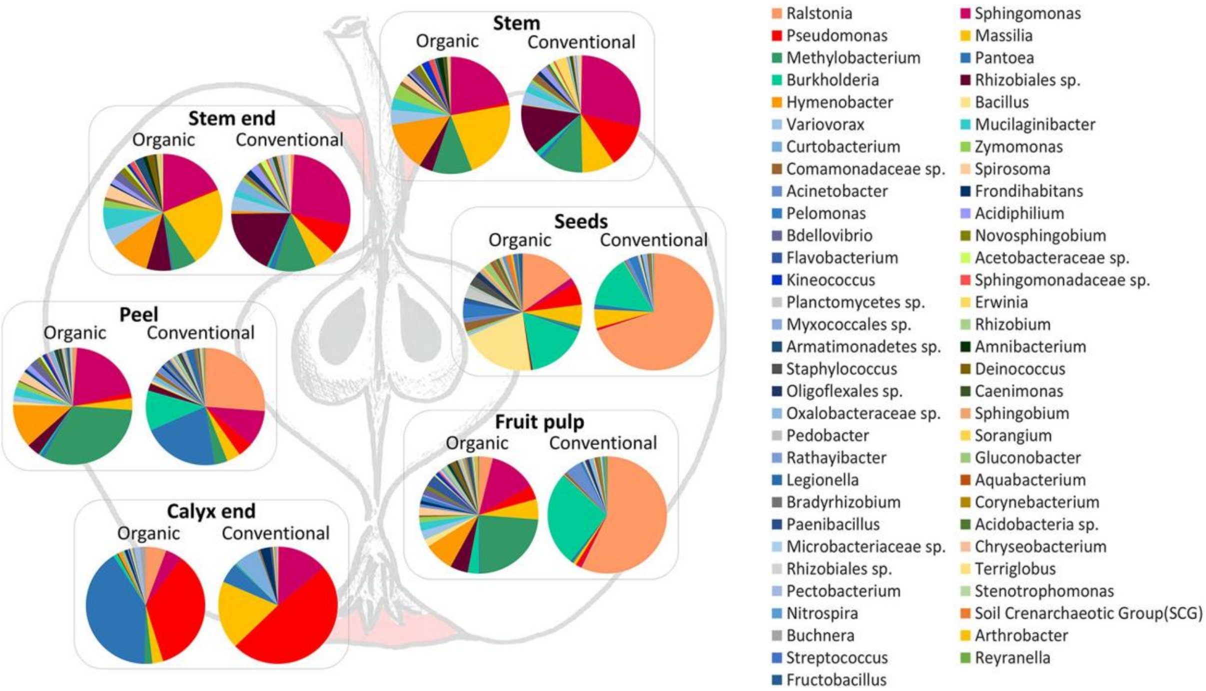


Image from reference[27] : Taxonomic composition of organic and conventional apple tissue microbiota.

Future directions

While early findings suggest that soil health influences both nutrient density and microbial richness in food, much more research is needed to fully understand these relationships. As we continue to uncover the connections between soil, food and health, it is becoming increasingly clear that healthy soils grow healthier food, which in turn supports healthier people. Understanding and optimising farming practices to improve soil health could be a game-changer for both agriculture and public health.

5.2 CROP GENETICS AND NUTRIENT DENSITY

During my travels, it became clear from conversations with plant breeders that genetic diversity plays a significant role in determining the nutrient quality of food. While modern crop breeding has focused on yield, pest and disease resistance, and growth rate, nutritional value has seldom been a primary selection criterion. However, research suggests that genetic variation can lead to substantial differences in nutrient content, even among crops grown under the same conditions.

One study found a **2-fold difference in calcium content** and a **1.5-fold difference in magnesium content** between different broccoli varieties.[28] Notably, mineral concentrations were found to be inversely correlated with yield, meaning that as head weight increased, nutrient density decreased.

In a further study of 50 broccoli varieties, researchers found dramatic differences in concentrations of beneficial phytochemicals including:[29]

- Alpha-carotene: 3.5-fold variation.
- Beta-carotene: 4-fold variation.
- Alpha-tocopherol (Vitamin E): 9-fold variation.
- Gamma-tocopherol: 22-fold variation.
- Ascorbate (Vitamin C): 2.8-fold variation.

A market blind to nutrition

The problem is not that genetics impact nutritional quality; rather that we place little value on these differences. Since market demand does not prioritize nutrient density, breeders have little incentive to select for it. As a result, modern crop varieties continue to be bred primarily for yield, often at the expense of nutrition. This trade-off was emphasized by the Broadbalk experiment at Rothamsted, which showed how breeding for productivity had inadvertently reduced the nutrient density of wheat. Despite this trend, breeding techniques can be used to enhance the nutritional content of crops whilst maintaining good yields and agronomic properties. Plant breeding can improve food quality in three key ways:

1. **Enhancing nutrient uptake**: Selecting for varieties that absorb and retain more minerals from the soil.
2. **Reducing antinutrients**: Lowering levels of compounds like phytates, which hinder mineral absorption.
3. **Boosting nutrient bioavailability**: Increasing compounds that enhance absorption, such as nicotinamide, which improves iron and zinc uptake.

Traditional breeding for nutrient-rich crops

One leading initiative I discovered at the Global Micronutrient Forum is **HarvestPlus**, a programme that has spent 25 years breeding staple crops with higher levels of essential vitamins and minerals to combat malnutrition. By using conventional breeding methods, they identify naturally nutrient-rich varieties and cross them with high-yielding cultivars. This approach has led to the development of more than 400 nutritionally enhanced staples, now cultivated in at least 40 countries world-wide. Examples include:

- **High Vitamin A** sweet potatoes, maize, and cassava.
- **High Iron** beans and pearl millet.
- **High Zinc** rice and wheat.

The positive impact of consuming biofortified crops is becoming increasingly clear. Studies show that eating these enhanced varieties leads to significant improvements in micronutrient status and cognitive function:

- In Rwanda, female university students consuming iron-rich beans for 4.5 months experienced increased iron levels, which improved memory, attention and physical performance.[30]
- In Maharashtra, India, adolescents who ate iron-fortified pearl millet for four months showed enhanced iron status along with improvements in memory and attention.[31]

While biofortified crops will undoubtedly be most valuable in developing nations facing severe nutrient deficiencies, they could also provide cost-effective benefits in developed countries. Even populations consuming a generally adequate diet still experience micronutrient shortfalls.

Of course, how crops are processed also plays a crucial role in determining their nutritional value. For example, whole wheat flour contains far more iron and zinc than white flour (*28.2mg/kg* vs *6.7 mg/kg* of iron; *28.6mg/kg* vs *8.4 mg/kg* of zinc).[32] Similarly, fermentation processes such as sourdough baking can increase mineral bioavailability by breaking down phytates, which otherwise inhibit micronutrient absorption.

The potential of genetic engineering

While traditional breeding has been effective in improving crop nutrition, genetic engineering offers additional tools. However, public scepticism and regulatory restrictions have limited its application. Perhaps we need to debate the careful and considered use of these technologies to boost the nutritional content of food, whilst remaining alert to the unintended consequences of genetic modification. Some successful developments include:

- **GABA-enriched tomatoes:** The first CRISPR-edited food to enter the market. 'Sicilian Rouge' tomatoes are genetically edited to contain higher amounts of γ-aminobutyric acid (GABA), which is a molecule thought to help lower blood pressure, and are now commercially available in Japan.[33]
- **Iron-bioavailable rice**: Created through transgenic technology. The grains have an increased level of **nicotinamide**, a molecule that increases the bioavailability of iron in the rice. Though not yet commercially viable due to low yields, this research highlights the potential of genetic modification.[34]

Perennial crops: The future of sustainable nutrition?

A particularly exciting area of research is the development of perennial grains, which offer environmental and nutritional benefits. During my visit to **The Land Institute in Kansas, USA**, I met Wes Jackson and the team who are working on **Intermediate Wheatgrass (IWG)**, also known as **Kernza®**—a perennial cousin of wheat. Unlike conventional wheat, Kernza® does not require annual tilling and replanting. Kernza® is now marketed and consumed on a commercial scale.

The purpose for breeding IWG was to tackle environmental issues associated with annual cropping including soil degradation, water contamination and biodiversity loss. However, preliminary studies suggest that Kernza® may also be **nutritionally superior to wheat**, with:[35]

- 50% more protein.
- 129% more fibre.
- Higher levels of calcium, iron and potassium.
- Greater concentrations of polyphenols, including lutein, antioxidants and phenolics.[36]

These differences could be a consequence of the incredibly extensive root structure that these plants develop, with **15 times greater root growth** than annual wheat. IWG produces much smaller grains than wheat plants, which may also explain the higher concentration of protein and minerals. As discussed, certain compounds in grains, such as fibres, tannins and phytic acid, can reduce the bioavailability of minerals, therefore further research is needed to determine the bioavailability of minerals in Kernza® and fully assess the potential benefits for human health.

As breeding efforts for IWG continue, scientists are working to increase seed size and yield to make Kernza® more commercially viable. However, history has shown that increasing crop yields often comes at the expense of nutritional quality. A promising shift is that today's breeders are far more aware of the importance of nutrient density, offering hope that future varieties will strike a better balance between productivity and nutrition.

Lessons from wild foods

The superior nutrient density of wild foods provides further evidence that modern crop breeding has altered nutritional composition. A study on Finnish berries, for example, found that wild berries contained significantly higher levels of manganese than their commercially grown counterparts.[6] This highlights the need to **preserve genetic diversity** in our food supply and reconsider how we select crops for cultivation.

Of roughly 50,000 species of edible wild plants on earth, only fifteen account for 90% of the world's food energy intake, with rice, maize and wheat making up twothirds of this.[37] The rapid rate at which we have lost diversity in our diets has likely had a detrimental impact on our overall nutrition, with the loss of naturally nutrient-dense foods.

Future directions

Crop genetics play a crucial role in shaping the nutrient density of our food. While modern breeding has often prioritized yield over nutrition, there is growing recognition that we need to **breed for both productivity and health**. By leveraging traditional breeding, learning from wild and perennial foods, and even implementing genetic engineering, we can grow crops that nourish people more effectively.

5.3 AGRONOMIC BIOFORTIFICATION: ENHANCING NUTRIENT DENSITY AT THE FARM LEVEL

While healthy, living soils and good genetics can improve a plant's nutritional density, there is a fundamental limitation: if a particular mineral is deficient in the soil, plant assimilation will be poor, and consequently it will be lacking in our diet. This is especially concerning for staple crops such as grains and tubers, which form the foundation of many diets worldwide. Addressing this issue at the farm level by applying fertilisers containing essential nutrients could significantly improve the mineral content of plant-based foods.

The process of enhancing the nutritional value of food through agricultural interventions is known as **biofortification**. There are two main types:

1. **Genetic biofortification**: selective breeding or genetic engineering to develop nutrient-rich crop varieties.
2. **Agronomic biofortification**: application of nutrients to the soil or to plants as foliar sprays to enhance a plant's nutritional content.

While the previous section explored genetic biofortification, this section focuses on **agronomic biofortification**, which has proven to be an effective strategy in various countries.

Selenium biofortification in Finland: A success story

One of the best documented examples of biofortification comes from Finland, where a nationwide effort successfully addressed selenium deficiency. Selenium is an essential mineral for immune function, thyroid health and antioxidant activity.[38] In the 1960s, the Finnish government identified that the country's soils were **extremely low in selenium**, leading to widespread deficiencies in both humans and livestock. By the 1970s, the average daily selenium intake among the Finnish population was just **25 µg**, well below the EU recommendation of **55 µg**.[39] As a result, Finland had some of the lowest blood selenium levels in the world.

This deficiency was of particular concern due to selenium's role in our health. Research has associated low selenium intake with:

- Increased risk of **cardiovascular disease**.[40]
- Higher incidence of **gastrointestinal, lung and haematological cancers**. [41]
- **Weakened immune function**, with studies showing that during the COVID-19 pandemic, individuals with adequate selenium levels had lower mortality rates when infected with COVID-19.[42]

As a solution, the Finnish Ministry of Agriculture made it compulsory in 1984 to **add sodium selenate to agricultural fertilizers**. The impact was rapid and significant: within five years, the selenium concentration in Finnish-grown wheat, oats, and barley **increased 20- to 30-fold**.[39] Ongoing monitoring programmes have allowed for refinements in selenium application, ensuring that levels remain optimal. Between 1970 and 2010 average blood selenium levels in the Finnish population rose from *0.63–0.76 μmol/L* to *1.4 μmol/L*. The latest regulations, introduced in 2012, allow for 10 g Se per hectare in soil fertilizers and 4 g Se per hectare in foliar fertilizers.[39]

This example demonstrates how targeted nutrient application at the farm level can effectively **correct nationwide deficiencies** and improve public health.

Zinc biofortification: Addressing a global deficiency

Zinc is another essential mineral with multiple physiological roles, including **immune function, reproduction, growth and cardiovascular health**. Research has linked adequate zinc intake to a reduced risk of **type 2 diabetes and cardiovascular disease**. However, in parts of China, Pakistan and India, soils are naturally depleted in zinc, resulting in low concentrations in staple foods.

In China, wheat contributes about 20% of daily zinc intake, with an even higher proportion in rural northern areas.[43] However, wheat grown in soils deficient in zinc does not provide sufficient levels of this crucial nutrient. Agronomic biofortification using **solid fertilizers enriched with zinc** or **foliar sprays** has been shown to be highly effective, increasing **grain zinc concentration between 39% and 73%**, depending on the rate of foliar application.[44]

Beyond human health, zinc deficiency in crops can impair plant growth and reduce yields. Trials in Pakistan found that zinc biofortification not only increased the zinc content in wheat but also improved economic returns for farmers due to better yields.[45] This dual benefit of enhancing nutrition while boosting agricultural productivity, makes zinc biofortification a particularly attractive intervention.

Molybdenum biofortification: A lesser-known but promising strategy

Molybdenum is an essential trace mineral involved in **enzyme function, mitochondrial activity and iron metabolism**. Natural sources include nuts, legumes and grains, but the concentration in these foods depends on its availability from the soils these plants are grown in.

A study in Italy examined the impact of molybdenum biofortification on human health. Researchers grew lettuce enriched with molybdenum, which contained **8 mg/100 g** – a dramatic increase from the **0.21 mg/100 g** found in conventionally grown lettuce. When participants consumed this biofortified lettuce over 12 days, their **serum molybdenum levels increased by 42%**. Additionally, researchers observed:

- Improved blood iron levels, suggesting potential benefits for iron homeostasis.[46]
- Better fasting glucose levels and lower insulin resistance, indicating possible benefits for metabolic health.[47]

These findings suggest that molybdenum biofortification could be explored as an **alternative to iron supplementation** for individuals with low iron.

Future directions

Despite compelling evidence from Finland, China, Pakistan and Italy, **agronomic biofortification is not routinely practiced in the UK**, nor is there significant research into its potential as a national public health strategy. Targeted programmes within UK agricultural policy could offer a **cost effective, scalable solution** to tackling micronutrient deficiencies, improving public health and improving crop yields.

Staple crops such as **wheat and potatoes** could be enriched with essential minerals like **zinc, selenium and iodine**, creating a more nutrient-dense food system and addressing widespread nutrient deficiencies specific to our UK population.

5.4 LIVESTOCK MANAGEMENT PRACTICES AND NUTRITIONAL QUALITY OF ANIMAL PRODUCTS

Through my travels, I found the **strongest evidence linking farming practices and food nutrition centred around livestock**. How we feed and raise livestock directly affects the nutritional composition of meat, dairy and eggs – particularly in terms of omega-3 and omega-6 fatty acids and phytochemicals.

The importance of Omega-3 and Omega-6 in human health

Omega-3 and omega-6 fatty acids are both essential polyunsaturated fatty acids (PUFA), meaning our bodies cannot produce them: we must obtain them from our diet.

Omega-3 fatty acids include:

- Long chain acid: ALA (Alpha-Linolenic Acid), found in plant sources such as flaxseeds and walnuts.
- Very long chain acids: EPA (Eicosapentaenoic Acid), DHA (Docosahexaenoic Acid) and DPA (Docosapentaenoic Acid) found in marine and animal products.

The role of omega-3:

- **Brain function and mental well-being:** low omega-3 levels are correlated with higher rates of depression and cognitive decline.
- **Cardiovascular health:** blood concentrations of omega-3 can predict risk of cardiovascular disease.[48]
- **Reducing inflammation:** helping to reduce autoimmune disorders, arthritis and other chronic inflammatory conditions.[49]

Omega-6 fatty acids include:

- Long chain acid: LA (Linolenic Acid), found in seeds, nuts and plant oils.
- Very long chain acid: AA (Arachidonic Acid), found in animal products.

The role of omega-6:

- **Skin health:** Omega-6 is needed to produce skin cells and maintain a good skin barrier.[50]
- **Cardiovascular health:** Omega-6 intake can help reduce blood total cholesterol and LDL cholesterol. Replacing 5% of dietary saturated fat with omega-6 results in a 9% reduced risk of cardiovascular disease.[51]

Both omega-3 and omega-6 fatty acids are essential for human health, but both their **balance and quantity in the diet matter**. The modern Western diet has an omega-6 to omega-3 ratio of 15-20:1,[52] a stark contrast to the estimated 1:1 ratio of our Paleolithic ancestors.[53] This shift is largely due to **increased consumption of foods rich in omega-6** such as grains and vegetable oils, alongside a **decline in consumption of omega-3** sources like fish, pasture-raised meat and dairy. As a result, many people fail to meet recommended omega-3 intake: one French study found that women of childbearing age consumed only 40% of the daily recommendation.[54]

Long chain omega-3 (ALA) and long chain omega-6 (LA) fatty acids rely on the same enzyme pathway to be converted into their biologically active very long chain forms. Since they compete for this process, excessive omega-6 intake can reduce the body's ability to convert and utilize omega-3. Given that modern diets heavily favour omega-6 consumption, it's unsurprising that average blood levels of the very long chain omega-6 Arachidonic Acid (AA) far exceed those of the very long chain omega-3 Eicosapentaenoic Acid (EPA) and Docosahexaenoic Acid (DHA).[55]

We must urgently consider whether this dietary imbalance is contributing to rising rates of chronic inflammation, heart disease and metabolic disorders.

The changing nutritional profile of chicken meat

It is not just our human diets that have changed over recent history. The genetics and feeding practices of livestock have altered dramatically.

Chicken consumption has risen significantly due to its reputation as a lean, heart-healthy protein source. However, modern intensively farmed chickens differ nutritionally from those of past decades.

A study comparing UK chickens from the **1970s to 2004** found that:[56]

- **Modern chickens are larger**: a 2004 chicken thigh contained 100 kcal more than its' 1970s equivalent.
- **DHA omega-3 content has plummeted** from 170mg/100g in the 1970s to just 25mg/100g in 2004. To obtain the same amount of DHA from modern chicken, you would have to eat six times as much meat.

This shift means modern chickens are **higher in calories and lower in beneficial nutrients like omega-3.** These changes are largely due to several factors including selective breeding for rapid growth, creating larger, fattier birds, giving birds constant access to high-energy feed rather than the more varied diet of pastured or wild birds and less exercise, which affects muscle composition.

Rethinking animal diets: Enhancing omega-3 content

There is strong evidence that **adjusting livestock diets** can **improve the fatty acid profile** of animal products. Forages such as grasses and herbs are naturally high in omega-3, whereas grains are high in omega-6. The amount these feeds contribute to the animals' diet will impact the omega-3 and omega-6 content of the meat and dairy products.

Poultry and Pigs

- **Linseed, rapeseed and fish oil supplementation** have been shown to **increase omega-3 content** in poultry meat and eggs while reducing omega-6.[57]
- A study found that feeding pigs a mix of rapeseed, linseed and fish oil resulted in omega-6:3 ratios of between 3:1 to 5:1, compared to 17:1 in pigs on standard grain-based diets.[58]
- Feeding hens linseed oil increased ALA in eggs in a dose-dependent manner.[59]
- Wild Cretan Greek eggs had an omega-6:3 ratio of 1.3:1, compared to 19.9:1 in industrial eggs – likely due to natural foraging on snails, slugs and purslane.[60]

Beef and Dairy

- **Grass-fed beef** contains **2-3 times more EPA, DPA and DHA omega-3s** and has a healthier **omega-6:3 ratio** than grain-fed beef.[61]
- **100% grass-fed cow's milk** has:
    - **147% higher omega-3** than milk from conventional 'total mixed ration' (TMR) production systems.
    - **52% higher omega-3** than milk from organic production systems, where cattle have some access to fresh forage.
    - A significantly improved omega-6 to 3 ratio: 5.8:1 (TMR), 2.3:1 (organic), 0.95:1 (100% grass-fed).[62]

Going beyond fatty acids

Omega-3s are just one piece of the puzzle; meat and dairy products contain thousands of **phytochemicals** that influence our health. Phytochemicals pass from plants to animals to us, via the animals' diet. These phytochemicals can have anti-inflammatory, antioxidant, anti-viral and anti-cancer properties, and they are critical for the health of humans and animals.

- Beef from cattle raised on **diverse plant pastures** had higher levels of phytochemicals - **terpenoids, phenols, carotenoids, and tocopherols** - compared with beef from cattle grazing monoculture pastures or grain-based diets.[63]
- The yellow fat in grass-fed beef and dairy indicates greater **carotenoid content**, obtained from fresh forages. Feeding conserved forage may not have the same impact: converting fresh grass to silage, haylage or hay can reduce the carotenoid content by as much as 80%.[64]

Eating meat and dairy rich in phytochemicals could expand our intake of plant-derived compounds that we might not otherwise consume. Future research should compare the health impacts of meat from diverse pastures, monoculture pastures and grain-fed systems. The Bionutrient Institute and Professor Stephan Van Vliet are currently investigating how farming methods influence nutrient and phytochemical content in beef. Their findings will provide valuable insights to inform the livestock sector how to optimise farming for more nutrient-dense animal products.

Proving the human health benefits

While nutritionally enhanced animal products are promising, their health benefits must be demonstrated in human trials. Early research suggests that:

- People fed grass-fed beef for four weeks had significantly increased blood levels of the omega-3 DPA and EPA, compared with the group fed grain-finished beef.[65]
- People fed pecorino cheese made from sheep who foraged on diverse pastures in Tuscany, Italy for 10 weeks showed reduced levels of inflammatory cytokines (IL-6, IL-8 and TNF-alpha) and reduced platelet aggregation; both measures indicative of improved levels of inflammation.[66]
- People fed meat, dairy and eggs from animals whose diet was supplemented with omega-3 via the inclusion of linseed, had significantly higher blood levels of omega 3, and an improved omega-6 to omega-3 ratio.[67]

These findings hint at potential long-term health benefits, but longer-term trials are likely needed to understand the full effect.

Future directions

Animal nutrition is a powerful lever for improving human health. By modifying livestock diets, we can enhance the omega-3 content and phytochemical richness of animal products, rebalance our dietary omega-6:3 ratio, and potentially reduce the risk of chronic diseases.

The challenge now is to bridge the gap between science and consumer demand, creating a food system that prioritises nutrition.

CHAPTER 6: BRINGING IT TO MARKET: HOW TO INCREASE DEMAND FOR MORE NUTRIENT DENSE FOODS

The final question I had in mind throughout my Nuffield travels was how farmers could be fairly and financially rewarded for producing more nutrient-dense foods. Who should pay for the true nutritional value of food? I believe people innately care about their health and the food that they eat. In consumer surveys, health often ranks as the number one priority when shopping for food. The challenge, then, is connecting consumer demand with farming practices that enhance nutrient density and ensuring that farmers see a financial return for their efforts. I explored several innovative approaches that aim to make nutrient density a valuable market differentiator.

Empowering consumers through transparency

The **Bionutrient Institute** believes that market demand will ultimately drive farmers to adopt nutrient-enhancing practices. Their vision is to develop a handheld scanning device – possibly even incorporated into a mobile phone – that would allow consumers to scan food in real time and assess its nutrient density. This would put power directly in the hands of shoppers, enabling them to make more informed choices and select the most nutrient-dense produce available.

Another approach is to develop **predictive models** that use easily measurable farm data, such as soil organic matter, soil CO_2 burst test results and mineral analysis, to reliably estimate nutrient density. Farmers could use this data to qualify their produce as nutritionally superior, creating a marketing advantage without the need for expensive lab testing of every batch of food.

The value of connecting with consumers

During my travels, one of the most inspiring experiences was visiting **Joel Salatin's Polyface Farm** in Virginia, USA. His regenerative system integrates mob grazing, agroforestry and composting to restore ecological health. At a farm open day, I joined around 200 visitors who had come to hear Joel speak passionately about his farming methods. Recognizing that his practices likely enhance the

nutritional quality of his produce, Joel has started testing his food and sharing the results directly with customers.

This experience reinforced the power of **farmer-to-consumer relationships**. By offering farm tours, sharing stories and providing transparency about production methods, farmers can cultivate trust and educate consumers about the benefits of nutrient-dense foods.

I saw a similar model at **Dan Barber's Blue Hill restaurant at Stone Barns** in New York, where diners take a two-hour farm tour before their meal to understand how their food has been grown. Barber is breeding new fruit and vegetable varieties for better flavour, and interestingly his early testing reveals that foods with more intense flavour may have higher nutrient density. By engaging directly with his customers, he can share these findings and emphasise the link between farming, flavour and nutrition.

Financial reward at scale: The Bleu-Blanc-Cœur model

The most successful large-scale model I found was **Bleu-Blanc-Cœur** in France, co-founded by Pierre Weill. Bleu-Blanc-Cœur operates a certification system for farmers who feed their animals a diet rich in omega-3 sources, such as grass, flaxseed and lucerne. In return, these farmers can use the Bleu-Blanc-Cœur logo, signalling to consumers that their products: meat, milk, and eggs, are naturally enriched with omega-3.

Image from https://international.bleu-blanc-coeur.org/

Bleu-Blanc-Cœur collaborates with universities, hospitals and nutritionists to measure the human health benefits of omega-3-enriched foods. By clearly communicating these benefits to consumers, it has built strong demand for its certified products, allowing farmers to earn a price premium for their nutrient-rich produce.

The success of this model is striking; Bleu-Blanc-Cœur now works with more than 7,000 farmers. Its approach, linking farming practices to human health and establishing a certification system, demonstrates a viable path for rewarding farmers who produce more nutrient-dense foods.

Biofortification: A market-driven approach

Another intriguing example I found was **selenium-enriched apples** in Germany. Apples are widely consumed, making them an excellent vehicle for agronomic biofortification.

Consumer response has been positive:

- A German study found that consumers preferred apples biofortified with both iodine and selenium over those enriched with only one micronutrient.[68]
- Many consumers stated that they would rather get essential nutrients from food than supplements.[69]

This suggests that agronomic biofortification could be an effective strategy for improving public health while also creating a **market advantage** for farmers who adopt it.

Stacking functions: A holistic approach

The opportunity to financially reward farmers for better nutrition extends beyond price premiums; it also aligns with soil health benefits. Many of the practices that improve soil health also increase soil carbon storage, biodiversity and resilience to climate change. By stacking these benefits, we create a system that supports healthier soils, healthier food and healthier people.

I was excited to hear of the **One Health** concept at the European Public Health Conference in Dublin. It is the idea that the **health of people, animals and the environment are deeply interconnected**. I was reminded of a quote from 1943 from Lady Eve Balfour, a key founder of the organic farming movement in the UK, that sparked my desire to apply for a Nuffield Farming Scholarship:

"The health of soil, plant, animal and man is one and indivisible."

I think there is still a long road ahead to achieve true collaboration between the agricultural and the health sector; currently it seems that the two operate in silos.

However, it is greatly encouraging to hear the public health sector embracing the concept of One Health. We need the agricultural sector to acknowledge that not all food production systems are the same and to offer solutions to the public health sector for the provision of nutrient-dense foods, with the appropriate reward mechanisms in place for farmers. Adopting this strategy could help to advance the health of both people and planet.

CHAPTER 7: RECOMMENDATIONS AND CONCLUSION

After two years of research and exploration, I am convinced that the link between farming, nutrition and health holds immense potential, but we are still in the early stages of truly understanding it. To make meaningful progress, we need robust research, consumer engagement and a financial model that fairly rewards farmers for producing nutrient-dense foods.

Invest in further research

While the body of evidence connecting farming methods and human nutrition is growing, there are still critical gaps in our understanding. To move forward with confidence and avoid making unsubstantiated health claims, we must prioritize targeted research in the following areas:

<u>Quantifying the impact of soil health on nutrient density.</u>

Rather than relying on broad farming labels such as organic or no-till, we need **measurable, science-backed indicators** of soil health that correlate with food nutrition. I propose that **soil organic matter, soil CO_2 respiration (soil microbial activity), and mineral content** be used as key metrics in future studies to establish a reliable link between soil health and nutrient density.

<u>Breeding for nutrient density.</u>

Historically, plant breeding has selected for yield, pest and disease resistance and transportability, perhaps inadvertently at the expense of nutrient content. We must encourage breeding programmes to **select for nutrient density** as a core trait. This will require **both market-driven demand and policy incentives** to make nutrient-rich varieties economically viable for farmers and breeders.

<u>Exploring the role of agronomic biofortification.</u>

To tackle micronutrient deficiencies in the UK – such as selenium and iodine – **biofortification may be a valuable tool** for public health. Further research is needed to assess its effectiveness and feasibility, as well as to develop strategies that integrate biofortification within sustainable farming systems.

<u>Nutrient profiling of animal products.</u>

The impact of livestock feeding systems on human health is still only partially understood. Beyond the grass-fed vs. grain-fed debate, we need research into **how greater plant diversity in livestock diets affects the nutritional composition of meat, milk and eggs**. Understanding these nuances could unlock new opportunities for improving food quality through regenerative livestock management.

Engage and educate consumers

Even as research advances, we must not wait to bring consumers along on this journey. People care deeply about their health and the food they eat, but they need **clear, accessible information** to make informed choices.

Transparency and nutrient testing.

As tools like handheld nutrient scanners and predictive models develop, we should explore ways to **communicate nutritional differences to consumers**. If consumers can see tangible proof of nutrient density, they are more likely to support farmers producing higher-quality food.

Recognisable certification systems and food labelling.

The certification system and labelling by Bleu-Blanc-Cœur is becoming well recognised by French consumers. This model could be applied to other nutrients and food products, helping to engage a wider consumer audience.

Farmer-to-consumer connections.

Experiences like **farm tours, open days and direct sales models** can help farmers build trust and understanding with their customers. **Joel Salatin's farm tours** and **Dan Barber's immersive dining experience** demonstrate the power of storytelling and firsthand experience in shaping food choices.

Prioritise soil health as a long-term strategy

Regardless of how quickly financial rewards for nutrient-dense foods materialise, improving soil health is a win-win for farmers. Healthy, microbially rich soils build resilience, increase carbon sequestration, boost biodiversity and enhance food quality. Whilst research continues, farmers should be encouraged to adopt practices that regenerate soil ecosystems. I remain optimistic that a future where farmers are fairly rewarded for the nutrients they provide is within reach.

Conclusion

Improving public health through nutrient-dense foods will require a multidisciplinary effort, bringing together expertise in agricultural research, human nutrition, public health and the farming community.

While dietary choices influence individual nutrient intake, the nutrient density of the foods available in our food system is equally crucial. Improving the nutrient density of foods will ensure that our diets contain the highest possible levels of essential nutrients and have a positive impact on our health.

The farming sector has a unique opportunity to be at the forefront of this movement. By implementing better soil management, more nutrient-focused breeding, appropriate agronomic biofortification and diverse pasture-based livestock systems we can shift the food system toward greater nutrient quality. With the right collaboration and consumer engagement, I believe this shift is within reach.

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CHAPTER 9: BIBLIOGRAPHY

1. Erenstein O, Jaleta M, Mottaleb KA, Sonder K, Donovan J, Braun HJ. Global Trends in Wheat Production, Consumption and Trade. In: Reynolds MP, Braun HJ, editors. Wheat Improvement: Food Security in a Changing Climate. Cham: Springer International Publishing; 2022. page 47–66.

2. Jelle Bruinsma et al. Prospects for food and nutrition. In: Jelle Bruinsma, editor. World Agriculture: Towards 2015/2030 - An FAO perspective. London: Earthscan Publications Ltd; 2003. page 29–54.

3. Drewnowski A, Fulgoni V. Nutrient profiling of foods: Creating a nutrient-rich food index. Nutr Rev 2008;66(1):23–39.

4. Mayer AM. Historical changes in the mineral content of fruits and vegetables. British Food Journal 1997;99(6):207–11.

5. Davis DR, Epp MD, Riordan HD, Davis DR. Changes in USDA Food Composition Data for 43 Garden Crops, 1950 to 1999. J Am Coll Nutr 2004;23(6):669–82.

6. Ekholm P, Reinivuo H, Mattila P, Pakkala H, Koponen J, Happonen A, et al. Changes in the mineral and trace element contents of cereals, fruits and vegetables in Finland. Journal of Food Composition and Analysis 2007;20(6):487–95.

7. Mayer AMB, Trenchard L, Rayns F. Historical changes in the mineral content of fruit and vegetables in the UK from 1940 to 2019: a concern for human nutrition and agriculture. Int J Food Sci Nutr 2022;73(3):315–26.

8. Fan MS, Zhao FJ, Fairweather-Tait SJ, Poulton PR, Dunham SJ, McGrath SP. Evidence of decreasing mineral density in wheat grain over the last 160 years. Journal of Trace Elements in Medicine and Biology 2008;22(4):315–24.

9. Garvin DF, Welch RM, Finley JW. Historical shifts in the seed mineral micronutrient concentration of US hard red winter wheat germplasm. J Sci Food Agric 2006;86(13):2213–20.

10. The Bionutrient Institute. The Bionutrient Institute 2020 Data Report [Internet]. 2020 [cited 2025 Apr 15];Available from: https://www.bionutrientinstitute.org/2020datareport

11. Stevens GA, Beal T, Mbuya MNN, Luo H, Neufeld LM, Addo OY, et al. Micronutrient deficiencies among preschool-aged children and women of reproductive age worldwide: a pooled analysis of individual-level data from population-representative surveys. Lancet Glob Health 2022;10(11):e1590–9.

12. Public Health England. National Diet and Nutrition Survey. Results from Years 7-8 (combined) of the Rolling Programme (2014/15 to 2015/16). PHE publications gateway number 2017851. London: 2018.

13. Rosanoff A, Dai Q, Shapses SA. Essential nutrient interactions: Does low or suboptimal magnesium status interact with vitamin D and/or calcium status? Advances in Nutrition 2016;7(1):25–43.

14. Rees A, Dodd GF, Spencer JPE. The effects of flavonoids on cardiovascular health: A review of human intervention trials and implications for cerebrovascular function. Nutrients 2018;10(12):1852.

15. Dinkova-Kostova AT, Kostov R V. Glucosinolates and isothiocyanates in health and disease. Trends Mol Med 2012;18(6):337–47.

16. Grabowska M, Wawrzyniak D, Rolle K, Chomczyński P, Oziewicz S, Jurga S, et al. Let food be your medicine: Nutraceutical properties of lycopene. Food Funct 2019;10(6):3090–102.

17. Van Der Heijden MGA, Bardgett RD, Van Straalen NM. The unseen majority: Soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. Ecol Lett 2008;11(3):296–310.

18. Haygarth PM, Ritz K. The future of soils and land use in the UK: Soil systems for the provision of land-based ecosystem services. Land use policy 2009;(26S):S187–97.

19. Montgomery DR, Biklé A, Archuleta R, Brown P, Jordan J. Soil health and nutrient density: preliminary comparison of regenerative and conventional farming. PeerJ 2022;10(e12848).

20. Carrara JE, Lehotay SJ, Lightfield AR, Sun D, Richie JP, Smith AH, et al. Linking soil health to human health: Arbuscular mycorrhizae play a key role in plant uptake of the antioxidant ergothioneine from soils. Plants People Planet 2023;5(3):449–58.

21. Beelman RB, Richie JP, Phillips AT, Kalaras MD, Sun D, Duiker SW, et al. Soil Disturbance Impact on Crop Ergothioneine Content Connects Soil and Human Health. Agronomy 2021;11(11):2278.

22. Smith E, Ottosson F, Hellstrand S, Ericson U, Orho-Melander M, Fernandez C, et al. Ergothioneine is associated with reduced mortality and decreased risk of cardiovascular disease. Heart 2020;106(9):691–7.

23. Mantegazza G, Gargari G, Duncan R, Consalez F, Taverniti V, Riso P, et al. Ready-To-Eat Rocket Salads as Potential Reservoir of Bacteria for the Human Microbiome. Microbiol Spectr 2023;11(1):e02970-22.

24. Wicaksono WA, Cernava T, Wassermann B, Abdelfattah A, Soto-Giron MJ, Toledo G V, et al. The edible plant microbiome: evidence for the occurrence of fruit and vegetable bacteria in the human gut. Gut Microbes 2023;15(2).

25. Lupatini M, Korthals GW, de Hollander M, Janssens TKS, Kuramae EE. Soil microbiome is more heterogeneous in organic than in conventional farming system. Front Microbiol 2017;7.

26. Wicaksono WA, Buko A, Kusstatscher P, Cernava T, Sinkkonen A, Laitinen OH, et al. Impact of Cultivation and Origin on the Fruit Microbiome of Apples and Blueberries and Implications for the Exposome. Microb Ecol 2023;86(2):973–84.

27. Wassermann B, Müller H, Berg G. An Apple a Day: Which Bacteria Do We Eat With Organic and Conventional Apples? Front Microbiol 2019;10.

28. Farnham M, Grusak M, Wang M. Calcium and Magnesium Concentration of Inbred and Hybrid Broccoli Heads. J Amer Soc Hort Sci 2000;125(3):344–9.

29. Kurilich AC, Tsau GJ, Brown A, Howard L, Klein BP, Jeffery EH, et al. Carotene, tocopherol, and ascorbate contents in subspecies of Brassica oleracea. J Agric Food Chem 1999;47(4):1576–81.

30. Haas JD, Luna S V., Lung'aho MG, Wenger MJ, Murray-Kolb LE, Beebe S, et al. Consuming iron biofortified beans increases iron status in Rwandan women after 128 days in a randomized controlled feeding trial. Journal of Nutrition 2016;146(8):1586–92.

31. Finkelstein JL, Mehta S, Udipi SA, Ghugre PS, Luna S V., Wenger MJ, et al. A randomized trial of iron-biofortified pearl millet in school children in India. Journal of Nutrition 2015;145(7):1576–81.

32. Tang J, Zou C, He Z, Shi R, Ortiz-Monasterio I, Qu Y, et al. Mineral element distributions in milling fractions of Chinese wheats. J Cereal Sci 2008;48(3):821–8.

33. Waltz E. Japan embraces CRISPR-edited fish. Nat Biotechnol 2022;40(10):9–11.

34. Zheng L, Cheng Z, Ai C, Jiang X, Bei X, Zheng Y, et al. Nicotianamine, a novel enhancer of rice iron bioavailability to humans. PLoS One 2010;5(4):e10190.

35. Craine EB, DeHaan LR. Nutritional Quality of Early-Generation Kernza Perennial Grain. Agriculture 2024;14(6):919.

36. Bharathi R, Muljadi T, Tyl C, Annor GA. Progress on breeding and food processing efforts to improve chemical composition and functionality of

intermediate wheatgrass (Thinopyrum intermedium) for the food industry. Cereal Chem2022;99(2):235–52.

37. FAO. Staple Foods: What do People Eat? In: Loftas T, editor. Food and People: Dimensions of Need. London: Banson; 1996.

38. Bjørklund G, Shanaida M, Lysiuk R, Antonyak H, Klishch I, Shanaida V, et al. Selenium: An Antioxidant with a Critical Role in Anti-Aging. Molecules 2022;27(19):6613.

39. Alfthan G, Eurola M, Ekholm P, Venäläinen ER, Root T, Korkalainen K, et al. Effects of nationwide addition of selenium to fertilizers on foods, and animal and human health in Finland: From deficiency to optimal selenium status of the population. Journal of Trace Elements in Medicine and Biology 2015;31:142–7.

40. Salonen J, Alfthan G, Huttunen J, Pikkarainen J, Puska P. Association between cardiovascular death and myocardial infarction and serum selenium in a matched-pair longitudinal study. The Lancet 1982;320(8291):175–9.

41. Salonen J, Alfthan G, Huttunen J, Puska P. Association between serum selenium and the risk of cancer. Am J Epidemiol 1984;120(3):342–9.

42. Moghaddam A, Heller RA, Sun Q, Seelig J, Cherkezov A, Seibert L, et al. Selenium deficiency is associated with mortality risk from COVID-19. Nutrients 2020;12(7):1–13.

43. Ma G, Jin Y, Li Y, Zhai F, Kok FJ, Jacobsen E, et al. Iron and zinc deficiencies in China: what is a feasible and cost-effective strategy? Public Health Nutr 2008;11(6):632–8.

44. Zhang YQ, Sun YX, Ye YL, Karim MR, Xue YF, Yan P, et al. Zinc biofortification of wheat through fertilizer applications in different locations of China. Field Crops Res 2012;125:1–7.

45. Rehman A, Farooq M, Ullah A, Nadeem F, Im SY, Park SK, et al. Agronomic Biofortification of Zinc in Pakistan: Status, Benefits, and Constraints. Front Sustain Food Syst 2020;4.

46. Baldassano S, Polizzi MR, Sabatino L, Caldarella R, Macaluso A, Alongi A, et al. A New Potential Dietary Approach to Supply Micronutrients to Physically Active People through Consumption of Biofortified Vegetables. Nutrients 2022;14(14):2971.

47. Vasto S, Di Gaudio F, Raso M, Sabatino L, Caldarella R, De Pasquale C, et al. Impact on Glucose Homeostasis: Is Food Biofortified with Molybdenum a Workable Solution? A Two-Arm Study. Nutrients 2022;14(7):1351.

48. Harris WS. The omega-3 index as a risk factor for coronary heart disease. Am J Clin Nutr 2008;87(suppl):1997S-2002S.

49. Simopoulos AP. The Mediterranean Diets in Health and Disease. Am J Clin Nutr 1991;54(4):771.

50. Djuricic I, Calder PC. Beneficial outcomes of omega-6 and omega-3 polyunsaturated fatty acids on human health: An update for 2021. Nutrients 2021;13(7):2421.

51. Farvid MS, Ding M, Pan A, Sun Q, Chiuve SE, Steffen LM, et al. Dietary linoleic acid and risk of coronary heart disease: A systematic review and meta-analysis of prospective cohort studies. Circulation 2014;130(18):1568–78.

52. Sanders T. Polyunsaturated fatty acids in the food chain in Europe. Am J Clin Nutr 2000;71(1):176S-178S.

53. Hibbeln JR, Nieminen LR, Blasbalg TL, Riggs JA, Lands WE. Healthy intakes of n-3 and n-6 fatty acids: estimations considering worldwide diversity. Am J Clin Nutr 2006;83(suppl):1483S-93S.

54. Combe N, Boué C. Apports alimentaires en acides linoléique et alpha-linolénique d'une population d'aquitaine. Oleagineux Corps gras Lipides 2001;8(2):118–21.

55. Walker CG, West AL, Browning LM, Madden J, Gambell JM, Jebb SA, et al. The pattern of fatty acids displaced by EPA and DHA following 12 months supplementation varies between blood cell and plasma fractions. Nutrients 2015;7(8):6281–93.

56. Wang Y, Lehane C, Ghebremeskel K, Crawford MA. Modern organic and broiler chickens sold for human consumption provide more energy from fat than protein. Public Health Nutr 2010;13(3):400–8.

57. Nuernberg K, Fischer K, Nuernberg G, Kuechenmeister U, Klosowska D, Eliminowska-Wenda G, et al. Effects of dietary olive and linseed oil on lipid composition, meat quality, sensory characteristics and muscle structure in pigs. Meat Sci 2005;70(1):63–74.

58. Waszkiewicz-Robak B, Szterk A, Rogalski M, Rambuszek M, Kruk M, Rokowska E. Nutritional value of raw pork depending on the fat type contents in pigs feed [pdf]. Acta Sci Pol Technol Aliment [Internet] 2015 [cited 2025 Apr 15];14(2):153–63. Available from: https://www.food.actapol.net/volume14/issue2/7_2_2015.pdf

59. Milinsk MC, Murakami AE, Gomes STM, Matsushita M, De Souza NE. Fatty acid profile of egg yolk lipids from hens fed diets rich in n-3 fatty acids. Food Chem 2003;83(2):287–92.

60. Simopoulos AP, Salem Jr N. n-3 fatty acids in eggs from range-fed Greek chickens. N Engl J Med 1989;321(20):1412.

61. Carrillo JA, He Y, Li Y, Liu J, Erdman RA, Sonstegard TS, et al. Integrated metabolomic and transcriptome analyses reveal finishing forage affects metabolic pathways related to beef quality and animal welfare. Sci Rep 2016;6:25948.

62. Benbrook CM, Davis DR, Heins BJ, Latif MA, Leifert C, Peterman L, et al. Enhancing the fatty acid profile of milk through forage-based rations, with nutrition modeling of diet outcomes. Food Sci Nutr 2018;6(3):681–700.

63. van Vliet S, Provenza FD, Kronberg SL. Health-Promoting Phytonutrients Are Higher in Grass-Fed Meat and Milk. Front Sustain Food Syst 2021;4:555426.

64. Chauveau-Duriot B, Thomas D, Portelli J, Doreau M. Carotenoids content in forages: Variation during conservation. Renc Rech Ruminants 2005;12.

65. McAfee AJ, McSorley EM, Cuskelly GJ, Fearon AM, Moss BW, Beattie JAM, et al. Red meat from animals offered a grass diet increases plasma and platelet n-3 PUFA in healthy consumers. British Journal of Nutrition 2011;105(1):80–9.

66. Sofi F, Buccioni A, Cesari F, Gori AM, Minieri S, Mannini L, et al. Effects of a dairy product (pecorino cheese) naturally rich in cis-9, trans-11 conjugated linoleic acid on lipid, inflammatory and haemorheological variables: A dietary intervention study. Nutrition, Metabolism and Cardiovascular Diseases 2010;20(2):117–24.

67. Weill P, Schmitt B, Chesneau G, Daniel N, Safraou F, Legrand P. Effects of introducing linseed in livestock diet on blood fatty acid composition of consumers of animal products. Ann Nutr Metab 2002;46(5):182–91.

68. Kleine-Kalmer R, Profeta A, Daum D, Enneking U. Pre-launch exploration of consumer willingness to purchase selenium- and iodine-biofortified apples—a discrete choice analysis of possible market settings. Nutrients 2021;13(5):1625.

69. Wortmann L, Enneking U, Daum D. German consumers' attitude towards selenium-biofortified apples and acceptance of related nutrition and health claims. Nutrients 2018;10(2):190.

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