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Nutritional density of foods produced from biodynamic, organic, and conventional land use systems – Phase 1

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Executive summary

Nutritional density of foods produced from biodynamic, organic, and conventional land use systems – Phase 1

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The first phase of this project aimed to understand what the current scientific body of evidence is regarding whether biodynamic and organic food production systems produce foods with greater nutritional density and phytochemical composition, compared to conventional production practices. This work included reviewing the scientific literature and other available reports and determine criteria and design principles to be used to measure and compare biodynamic, organic and conventional growing systems. The initial focus of review was a New Zealand setting but, because of the lack of available data, international data were gathered.

Foods are a made up of complex mixtures of many macro- and micronutrients, as well as other bioactives (e.g. phytochemicals), that are essential for the proper functioning of the human body and overall good health. Nutrient-dense foods are important for health because they deliver more of what the body needs for good health (i.e. vitamins, minerals, complex carbohydrates, protein and healthy fats) and less of what it does not need as much of (i.e. saturated fat, sodium and refined sugars). Nutrients are needed to build all the body tissues but are also essential for many healthy bodily functions such as a healthy immune system, lowering the risk of non-communicable diseases (e.g. diabetes, cardiovascular disease, osteoporosis), assisting with weight management, improving digestion and can also lead to better mental health.

Each food has its own distinct nutritional and phytochemical profile. Nutritional profiling, and specifically nutrient density measures, has been used in an attempt to assess the overall nutritional value, and hence potential health benefits, of foods. There are various different measures/tools that have been reported in the literature to quantify nutrient density. However, the relevance of any particular nutrient density measure in terms of an impact on human health depends on several things:

- which components are included (nutrients and phytochemicals)
- how those nutrients are expressed, e.g. per 100 g, per serve, per 100 kcal
- putting the data in the context in of dietary requirements
- if looking at a food, meal or diet level.

Nutrient density measures are probably more relevant at a dietary level than for an individual food but also depend on the purpose of using such a measure. No existing published nutrient density tool is probably appropriate for the study of impacts of growing practices on composition. This is because they are limited in which nutrients and phytochemicals are included and may not have sufficient granularity to distinguish changes in particular subsets of nutrients. The specifics of what should be included in a particular study will depend on the target crop(s) and the questions being asked.

Longitudinal research in the US and the UK has identified a potential decline in the nutritional content of food (specifically some minerals) over several decades, although this is debated and complex. The composition of foods is influenced by a range of different factors, including genetics and the growing environment as well as postharvest handling and storage. There is a general body of evidence that different growing practices do impact the concentrations of some nutrients, and particularly phytochemicals. The evidential link between growing systems and nutrient density of food is complex and very few studies have been conducted in a robust manner that account for the key variables. There is also a lack of multiple studies with the same crop to understand the consistency of findings. A very good conventional farmer can produce nutrient dense food, an organic farmer may not, and vice versa. Synthesising the totality of the evidence, some of the key findings to date are:

- The strongest evidence is for differences in the phytochemical composition, with significantly higher concentrations of phenolic compounds, such as flavonoids, in both biodynamic and organic crops compared to conventional crops. This results in higher in vitro antioxidant activity in these crops.
- Conventional crops have consistently been shown to have higher pesticide concentrations and higher nitrate concentrations than those grown organically (there are fewer studies with biodynamic crops but expectations are they would confer the same advantage as organic).
- In terms of micronutrients (i.e. vitamins and minerals), there is a small amount of evidence for higher concentrations of selected compounds with organics, but in some crops data are conflicting. Of particular note, vitamin C is sometimes higher in organically grown produce. There are too few robust studies with biodynamics to draw firm conclusions, but trends may be similar to standard organics.
- Based on current evidence, there appear to be limited studies showing an advantage of biodynamic and organic practices on macronutrient composition (i.e. protein, fat, carbohydrate).
- Other growing practices (regenerative practices) may also deliver improvements in the nutrition and health benefits of crops without being strictly biodynamic or organic.

Differences in crop nutritional composition may relate to variation in the amounts of nutrients available to the plants and this may be impacted by growing practices. There are large differences in farming practices within all systems, meaning differences may or may not be seen when comparing any two particular farms. However, some generalisations can be made. Low nitrogen (N) concentrations in organic and biodynamic produce suggest that the amount of plant-available N applied is low, although nutrient budgets suggest that the amount of total N applied is greater than plant requirements. Studies have shown that the supply of phosphorus (P) and potassium (K) tends to be lower on organic and biodynamic farms than conventional farms for low-input systems. Phosphorus supply on biodynamic and organic intensive glasshouse and vegetable production systems is often excessive, although these intensive systems do not reflect the ethos of biodynamic farming. Organic and biodynamic systems are likely to supply more magnesium and trace elements than conventional systems, as these are contained in the compost and manures applied by organic and biodynamic growers, but not in the lime and N:P:K fertilisers commonly used in conventional farming. In terms of differences in nutrient availability, increases in organic matter and microbial activity may increase nutrient availability in organic and biodynamic systems compared with conventional systems where this nutrient is not supplied by a fertiliser.

The soil in which crops grow can have a significant impact on the quality of produce, including the nutritional composition. The general theme emerging from the literature suggests that biodynamic and organic management leads to elevated soil health and these practices generally promote more soil life than conventional growing systems. The improvements in soil health include greater functionally healthy microbial biomass, which allows plants to perform better physiologically with greater resilience to stress. This means they have a better chance to adsorb the nutrients they need to thrive, with this leading to a state of 'improved nutrient density' overall. Underpinning soil health is elevated soil organic matter, with the microbial biomass playing a key role in enhancing the plant-availability of the nutrients in this organic matter. Nutrient imbalances can occur in the soil, and yield deficits are common for biodynamic and organically managed systems compared to conventionally managed systems. Yield differences are most likely related to inadequacy of N availability but conversely this likely contributes to increased nutrient density and other desirable outcomes such as increased disease and pest tolerance and improved phytochemical profiles.

Consumers value foods in a number of ways. Food sustainability and food-related wellbeing are becoming an increasingly important conversation topic within society and for consumers. Aspects of biodynamic and organic agriculture that resonate most with consumers convey messages about soil, water, and biodiversity, with the influence of this production system on taste and consumers' personal health also being important. Notably, biodynamics is less recognised by consumers and therefore certification has a greater impact on price than, for example, foods produced by organic growers. The extent that consumers respond to nutritional information reflects familiarity with the nutrient and associated health benefit, and/or claim. A few studies have suggested that there is still considerable confusion and sometimes scepticism over health-related nutritional claims. A UK study on consumer perceptions indicated little detailed understanding of the term 'nutrient dense,' although it is perceived as being a positive attribute.

In conclusion, examining the totality of the evidence, there do appear to be some advantages of biodynamic practices in terms of increasing some aspects of nutrient density (at present primarily increases in phenolic concentrations) and improving aspects of the soil health. However, there are large gaps in the research when it comes to fully understanding the impacts of biodynamic growing practices on the composition, health benefits and sensory properties of foods, particularly in a New Zealand context. Even when comparing organic and conventionally grown produce, the evidence for an advantage of organics is not always consistent on some variables. Findings are not always consistent and there is a lack of multiple studies on the same crop with other parameters controlled to understand the reasons for differences. Thus, there is considerable potential for further research to understand and build the evidence base for the possible advantages of biodynamic and organic growing practices. The next steps for the project are to further refine what may be required in a future study.

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1 Objectives and approach

The first phase of this project aimed to understand whether biodynamic and organic food production systems produce foods with greater nutritional density and phytochemical composition compared to conventional production practices. Plant & Food Research (PFR) was asked to provide a considered view of the existing knowledge and publications which included:

- Reviewing past PFR reports and up to 20 published papers, targeting review papers where possible
- Determining criteria and design principles to be used to measure and compare biodynamic, organic and conventional growing systems
- A focus of the review being in a New Zealand setting but some consideration given to a global context.

The questions to be answered in the review, were:

1. What is a high nutrient dense food? Why are high nutrient dense foods beneficial to human health? [covered in Section 2 written by Carolyn Lister and Alison Wallace]
2. Is there a difference, and if so what is the difference in the nutrient and phytochemical content of foods grown using biodynamic methods compared with organic and conventional? [covered in Section 3 written by Alison Wallace and Carolyn Lister]
3. Which compounds are influenced to a greater degree by growing practice (micronutrients, macronutrients, phytochemicals)? [covered in Section 3 written by Alison Wallace and Carolyn Lister]
4. What nutrients are inputted and produced in biodynamic systems, compared to organic and non-organic[1] systems? [covered in Section 4 written by Stephen Trolove]
5. Does the microbial biomass of living soil in biodynamics, organics and conventional growing systems influence the nutrient density of food produced? [covered in Section 5 written by Craig Anderson]
6. What crops respond best to biodynamics with respect to nutrient content? [covered in Section 3.3 written by Stephen Trolove and Carolyn Lister]
7. Which nutrients do consumers care the most about? [covered in Section 6 written by Roger Harker]
8. What do consumers understand about biodynamics, compared to organics and conventional growing systems? What value do consumers place in biodynamic and organic food, compared with conventional food? [covered in Section 6 written by Roger Harker]

[1] For the purposes of this report we are referring to this as conventional growing practices.

2 Background

In recent years there has been an explosion of interest in more sustainable growing practices in order to achieve the United Nations Sustainable Development Goals (United Nations – Department of Economic and Social Affairs, Sustainable Development 2023). There is growing adoption of environmentally friendly methods in agriculture and horticulture as environmental stewardship is recognised worldwide (Dubey 2023; Khangura et al. 2023; O'Donoghue et al. 2022). A focus on what crops deliver in terms of their nutrition and health benefits is also important in the wider context of sustainability to deliver to SDG 3 'Good health and wellbeing', i.e. nutritional sustainability (Smetana et al. 2019). Strengthening the links between nutrition and sustainable food production systems and supply chains is necessary to deliver the improvements consumers are seeking in health and wellness. Some of the areas where sustainable food production interfaces directly with nutrition include crop production and breeding (Roberts & Mattoo 2019). Plant breeding is a longer-term solution but a focus on growing practices may achieve shorter-term delivery of more nutritionally dense foods. Sustainable farming practices include climate smart agriculture, organics, regenerative agriculture and biodynamics (Muhie 2022).

Biodynamics has received less attention than organics but is of growing interest. It is stated that "One of the most easily-seen and dramatic benefits of biodynamic practice is the exceptional quality of the produce: flavour, appearance and keeping quality are all enhanced" (Biodynamics New Zealand 2023). Similar claims have also been attributed to produce grown by regenerative practices and organics. The following section provides some definitions and parameters around the different growing systems.

There are various classifications being used for food produced by different growing practices including conventionally grown, regenerative agriculture and biodynamic certification. What is really the difference between regenerative farming versus biodynamic, or biodynamic versus organic in terms of production practices? The following section provides some definitions around these terms but we acknowledge that in the wider context these are not always so strictly defined and used. Each farming practice and method differs in what can and cannot be done, such as avoiding pesticides and other perceived harmful chemicals, and the degree of consideration of the long-term goal of improving the health of our soil and planet. In some cases the literature is clear on exactly the practices used but others are less well defined. Where possible we have noted key details around certification (or not).

2.1 Definitions: growing practices

2.1.1 Conventional growing practices

Generally, conventional farming (non-organic) has inputs of chemical synthetic fertilisers, herbicides, pesticides, feed additives and allows the use of genetically modified organisms (GMOs) (Hathaway-Jenkins et al. 2011; Giampieri et al. 2022), although the latter is country dependent and of course does not apply in New Zealand. Practices can vary hugely between different growers. Sometimes a few organic or regenerative practices may be applied but produce may not be certified organic as all criteria are not met.

2.1.2 Regenerative agriculture

Regenerative agriculture is a term that is being used more and more widely in recent years from growers through to retailers as well as politicians and the mainstream media. It has also been a topic of discussion in the research community, including in New Zealand (Grelet et al. 2021). Regenerative agriculture one of the alternative sustainable agricultures. Sustainable agriculture can be defined as *"an integrated system of plant and animal production practices having a site-specific application that over the long term will satisfy human food and fiber needs, enhance environmental quality and the natural resource base upon which, the agricultural economy depends, make the most efficient use of non-renewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls, sustain the economic viability of farm operations, and enhance the quality of life for farmers and society as a whole"* (Keeney 1990). While sustainable agriculture seeks to maintain and cease degradation of land, regenerative agriculture goes a step further and aims to restore land, promote soil health, and provide ecosystem services (Khangura et al. 2023; O'Donoghue et al. 2022). Regenerative agriculture also tries to reverse the effects of climate change, while sustainable agriculture tries to build resistance against climate change (Moyer et al. 2020).

There is no single internationally-used definition of regenerative agriculture. A recent review article examined 229 journal articles and 25 practitioner websites and revealed that there were many different definitions and descriptions of regenerative agriculture (Newton et al. 2020). They recommended that individual users define the term as necessary for their own purpose and context. This is probably sensible because regenerative agriculture encompasses a diverse range of management and agricultural techniques and practice, although there are some common principles and ethical commitments.

In general, regenerative agriculture describes holistic farming systems and is not a single method but in practice farmers incorporate a number of different sustainable agriculture approaches (Muhie 2022). The principles of regenerative agriculture generally include:

- reduction or elimination of the use of pesticides and synthetic fertilisers
- no tillage/minimum tillage in order to minimise the physical, biological, and chemical disturbance of the soil
- planting cover crops, using compost and animal manure, and working crop rotations into the annual plantings to help restore the soil and plant microbiome
- building ecosystem diversity
- well-managed grazing practices which also contribute to biodiversity, soil fertility and the soil microbiome.

As discussed by Grelet et al. (2021), regenerative agriculture has been proposed as a solution for some of Aotearoa New Zealand's most acute challenges. However, they highlighted the lack of evidence for some of the claims being made and the need for scientific testing of its claimed benefits. The white paper sets out 17 priority research topics identified by 200+ representatives of New Zealand's agri-food system for future work. There is probably some relevance of this work in the context of biodynamics.

At present there is no formal universal certification system for regenerative agriculture. There are some movements towards various possible systems but no international standard that has been accepted. An example of a recently developed certification system is the ‘Regenerative Organic Certified®’ which claims: “products meet the highest standards in the world for soil health, animal welfare, and farmworker fairness” (Regenerative Organic Alliance 2024).

In relation to the New Zealand context, there is no formal organisation with oversight over regenerative agriculture. Who decides what is considered ‘regenerative’ is being influenced primarily by supply chains (Quorum Sense 2024).

2.1.3 Organics

Organic farming is characterised by the prohibition of the use of chemical synthetic fertilisers, pesticides, growth regulators, and genetically modified organisms. In recent years there has also been emphasis on the application of sustainable agricultural technologies based on ecological principles and natural rules (Cahill et al. 2010; Giampieri et al. 2022). The International Federation of Organic Agriculture defines the term ‘organic agriculture’ as a production system that sustains the health of soils, ecosystems and people (International Federation of Organic Agriculture Movements (IFOAM) 2007). This involves the banned use of genetically modified material, synthetic mineral fertilisers, fungicides and pesticides. In addition, control measures are biological and natural, whereas conventional production methods allow the use of synthetic agricultural inputs (Mditshwa et al. 2017).

More specifically for New Zealand, the definition of organics is enshrined in legislation (https://www.mpi.govt.nz/agriculture/organic-product-requirements-in-nz). The specific requirements that will need to be met will depend on the market for the organic product (local or overseas). BioGro is New Zealand’s largest certification body for organic production (https://biogrow.co.nz/). Organic certification standards are not food safety standards and all organic products must also meet the same food safety standards that apply to all food for sale in New Zealand.

2.1.4 Biodynamics

Biodynamic agriculture is a form of organic agriculture pioneered by Dr Rudolf Steiner in the 1920s. Steiner believed a harmonious approach to farming would help support plants and animals, while creating nutrient-dense food and emphasizing self-sustainability (Kremsa 2021). Similar to organic farming, biodynamic agriculture avoids use of synthetic pesticides and herbicides, GMOs, hormones and other pharmaceutical growth promoters for livestock. Biodynamic agriculture and organic agriculture also share the practices of multiannual crop rotations, the use of mixed plants with mutual benefits and the use of compost made from animal manure. However, it is stated that biodynamic agriculture differs from organic agriculture in terms of involving specific practices aimed at improving plant vitality by strengthening plant, ground and environmental interactions (Kremsa 2021).

Biodynamics NZ (https://biodynamic.org.nz/) states that biodynamics takes a holistic view of the whole production unit: “Biodynamics is a systems approach, where the farm, vineyard, orchard or garden is viewed as a living whole and each activity affects everything else. Management is based on the grower’s own careful observations, plus the results of tests and analyses. In this way, modern technology and traditional knowledge marry to form a highly effective method that is unique to each location. Biodynamics uses very limited external inputs and re-uses most on-farm waste, so it has a low impact on the environment. It also provides an economical way of farming because most of the costs are met at the time they are incurred.”

Demeter is a worldwide certification system used to verify to the consumer that food or product has been produced by biodynamic methods. The Demeter Standards are a published statement of the allowed and the required practices for certified biodynamic operators (Demeter New Zealand 2021). According to these standards the principles include:

a) *application of sound organic principles;*

b) *development of an attitude of respect for and interest towards Nature;*

c) *the development of the farm, as far as possible, into a unique self-contained organism as the basic unit of a sustainable system, also called the farm individuality;*

d) *sustainable practices which maintain and increase fertility without the use of synthetic fertilisers and chemicals;*

e) *the keeping and breeding of healthy livestock in such a fashion that they are as far as possible able to perform all aspects of their innate behaviour;*

f) *positive care of the environment, efficient water use and the avoidance of pollution;*

g) *production of food of the highest nutritional quality;*

h) *development of a healthy and balanced cultural, social and economic environment;*

i) *development of associative business forms whereby a fair and equitable relationship is fostered between producer, distributor and consumer;*

j) *acknowledgement and working with the influences of the wider Earth environment including sun, moon, planets and fixed stars;*

k) *use of biodynamic preparations: These may be seen on one level as 'microbial inoculants' but can also provide the farmer with the opportunity for a more meditative approach and a chance to reflect upon and recognise the higher principles and various beings in Nature. Use of the biodynamic preparations aims to restore health to the farm individuality.*

2.2 Plant composition: Nutrients versus phytochemicals

Plant components can be differentiated into two key overarching groups, nutrients and phytochemicals. These two classes of components differ in a number of ways and these are summarised in Table 1. A nutrient is a substance that is required for growth or metabolism of living creatures. Plants absorb nutrients mainly from the soil in the form of minerals and other inorganic compounds, and we obtain nutrients from foods that we eat. Nutrients needed in very small amounts are called micronutrients (e.g. vitamins and minerals) and those that are needed in larger quantities are called macronutrients (e.g. protein, fat, carbohydrate). The effects of nutrients are dose-dependent and shortages are called deficiencies. A nutrient is said to be 'essential' when it must be obtained from food, either because we cannot synthesise it or our body cannot produce sufficient quantities. Essential nutrients have a recommended dietary intake (RDI). More details on the specific nutrients and their daily requirements are provided in Appendix 1. Nutrients are used to build and repair tissues, regulate body processes and are converted to and used as energy (see Appendix 2 for details on the well-established health benefits of nutrients). In addition to nutrients there are numerous other dietary compounds that may have various health benefits and reduce disease risk. Those compounds that are produced by plants are called phytochemicals (or sometimes phytonutrients, although they are technically not nutrients).

Table 1. Summary of key differences between nutrients and phytochemicals. RDI = Recommended Daily Intake.

	Nutrients	Phytochemicals
Human requirement	Essential for the maintenance of life and for growth but may also have additional health benefits	May be beneficial to human health and disease prevention but not regarded as essential for life; huge variation in likely amounts
Recognition	Long established	More recent emergence in scientific literature but slowly gaining recognition
Reference intakes	Exist (although amounts needed for some benefits may differ from RDIs)	Not yet established
Distribution	More widespread, although some restricted to certain food groups	Some classes can be very restricted to certain families only
Analysis methods	Well established; largely available through commercial laboratories and accredited	More complex and varied; usually not available through commercial laboratories and if are, not accredited methods
Claims permitted on products	Content claims and associated pre-approved health claims; comparative claims permitted for some nutrients	No claims beyond stating a product contains particular components and including on a nutrient information panel; no comparative claims

The term phytochemicals simply means plant compounds. It is commonly used to refer to the non-nutrients in plant-based foods that provide an array of health benefits, and in particular the plant pigments. There are thousands of different phytochemicals that have been found in plant foods and more are still being identified. The classes of phytochemicals include carotenoids, phenolic compounds (e.g. anthocyanins), chlorophyll, polysaccharides, terpenoids, phytosterols, glucosinolates/isothiocyanates, allium sulphur compounds, saponins, alkaloids and capsaicinoids (Asao & Asaduzzaman 2018; Gautam & Dwivedi 2022). The first three classes of compounds are widespread in their presence in plant tissues, although the specific compounds and concentrations vary, but others are narrow in their distribution and can be restricted to particular families of plants (e.g. capsaicinoids in the capsicum family). While phytochemicals are not essential dietary nutrients like vitamins and minerals, they contribute to the beneficial health effects which are linked with eating plant foods (Asao & Asaduzzaman 2018; Barros & Ferreira 2017; Martel et al. 2019; Mena & Angelino 2020). Antioxidant activity has been a focus as one mechanism of action for phytochemicals, however the emerging consensus is that although they are radical scavengers in vitro, they may not always function as antioxidants in our body. There are many possible mechanisms of action for phytonutrients to provide health benefits, including appropriate regulation of inflammation, neuroprotective effects, enhancement of immune responses, boosting of phase 2 antioxidant enzymes, and regulating energy metabolism and gut health.

2.3 Nutrient density

This section of the review is focused on the following questions:

- *What is a high nutrient dense food?*
- *Why are high nutrient dense foods beneficial to human health?*

2.3.1 What is nutrient density?

In developed countries, it is often stated that we are overfed but undernourished, because many people are consuming diets that are energy dense but nutrient poor (Drewnowski 2005). The term 'nutrient density' is often used in reference to diets but also sustainable agricultural practices such as regenerative agriculture (see Lister (2021) for discussion of nutrient density and food quality in this context) and biodynamics. Measures of nutrient density are also of increasing focus with the interest in conducting nutritional Life Cycle Assessments (nLCA) - defined as any LCA study in which nutrition is considered the main, or one of the main, functions of food (McLaren et al. 2021). However, the term nutrient density is not particularly well defined with enough granularity to be meaningful in all contexts. So, what does 'nutrient dense' mean? Usually, when a food presents a higher amount of important nutrients per unit of energy we tend to refer to it as being "more nutrient dense". Examples of nutrient-dense foods include fruits and vegetables, whole grains, low-fat or fat-free milk products, seafood, lean meats, eggs, peas, beans, and nuts.

Foods are a made up of complex mixtures of many macro- and micronutrients that are essential for the proper functioning of the human body (Katz-Rosene et al. 2023; also see Appendix 2). In addition, there are non-nutrients such as the phytochemicals (see section 2.2). Nutritional profiling, and specifically nutrient density measures, has been used to assess the overall nutritional value, and hence potential health benefits (e.g. Drewnowski et al. 2019, 2021). In these approaches, the nutritional value of foods, meals and/or diets is expressed in the form of indices featuring nutrients to encourage in the diet, nutrients to limit or a combination of both. Nutrient density scores can express the nutrient content of foods on the basis of a reference amount, (typically 100 kcal, i.e. on the basis of energy), per 100 g or per serving (Drewnowski & Fulgoni 2014). Various nutrient profiling systems have been developed in order to quantify the healthiness of foods to use for labelling as well as public health purposes in helping consumers with diet selections. Several different national and international standards have been developed and are in use for front-of-pack labels including 'traffic light' labels and Health Star Ratings. These differ in the breadth and depth of what components are included and some also differ in the scoring system used between food categories. Current food labelling indices are often more focused on nutrients to limit and are more applicable to processed foods and thus not of real value for fresh produce.

In addition, more detailed measures are used in research and dietary studies. Indices commonly used in nutritional studies include the Nutrient Quality Index (NQI), the Naturally Nutrient Rich (NNR) index and other Nutrient Density Scores (NDS) noted in Drewnowski (2005); the Overall Nutritional Quality Index (ONQI) (Katz et al. 2009, 2010); the Weighted Nutrient Density Score (WNDS) (Arsenault et al. 2012); the Mean Adequacy Ratio (MAR) and Mean Excess Ratio (MER) (Vieux et al. 2013); the SAIN:LIM ratio (Masset et al. 2014); and the Qualifying Index (QI), Disqualifying Index (DI) and the energy-standardised Nutrient Balance Concept using the QI (NBC) (Fern et al. 2015). Many of these are only applicable at a meal or diet level.

2.3.2 Why are high nutrient dense foods beneficial to human health?

Nutrient-dense foods are important for health because they deliver more of what the body needs for good health (i.e. vitamins, minerals, complex carbohydrates, protein and healthy fats) and less of what it does not need as much of (i.e. saturated fat, sodium and refined sugars). Nutrients are critical for both development and good overall health and wellness. Nutrients are needed to build bones, muscles, skin and all other body tissues. Better nutrition is also related to stronger immunity, lowers the risk of non-communicable diseases (e.g. diabetes, cardiovascular disease, osteoporosis), assists weight management, improves digestion and can lead to better mental health. Some of the specific well-established health benefits of individual nutrients are summarised in Appendix 2.

There are numerous papers in the literature providing evidence for increased intake of nutrient dense foods, both as part of the whole diet and also foods with specifically high nutrient density. A recent special issue of Foods 'Advances in Nutrient-Rich Foods for a Healthy Diet' had seven manuscripts, five original research studies, and two reviews (González-Palacios & Fonollá 2023). These papers assessed how nutrient-rich foods enriched in protein, fibre, vitamins, and minerals contributed to health and wellbeing, focusing on their composition, properties, and bioactive compounds, e.g., polyphenols. In another study, increased intake of foods with high nutrient density have also been shown to help to break the intergenerational cycle of malnutrition and obesity (Troesch et al. 2015).

It is not just nutrients that have an impact on good health; phytochemicals also have a range of health benefits and help reduce disease risk as discussed earlier. Some interesting work has also shown that landscapes with diverse phytochemical composition potentially improve the health of soils, the plants that grow on them, the animals that graze on them and so potentially improve the health of people and the environment (Figure 1; Provenza et al. 2019).

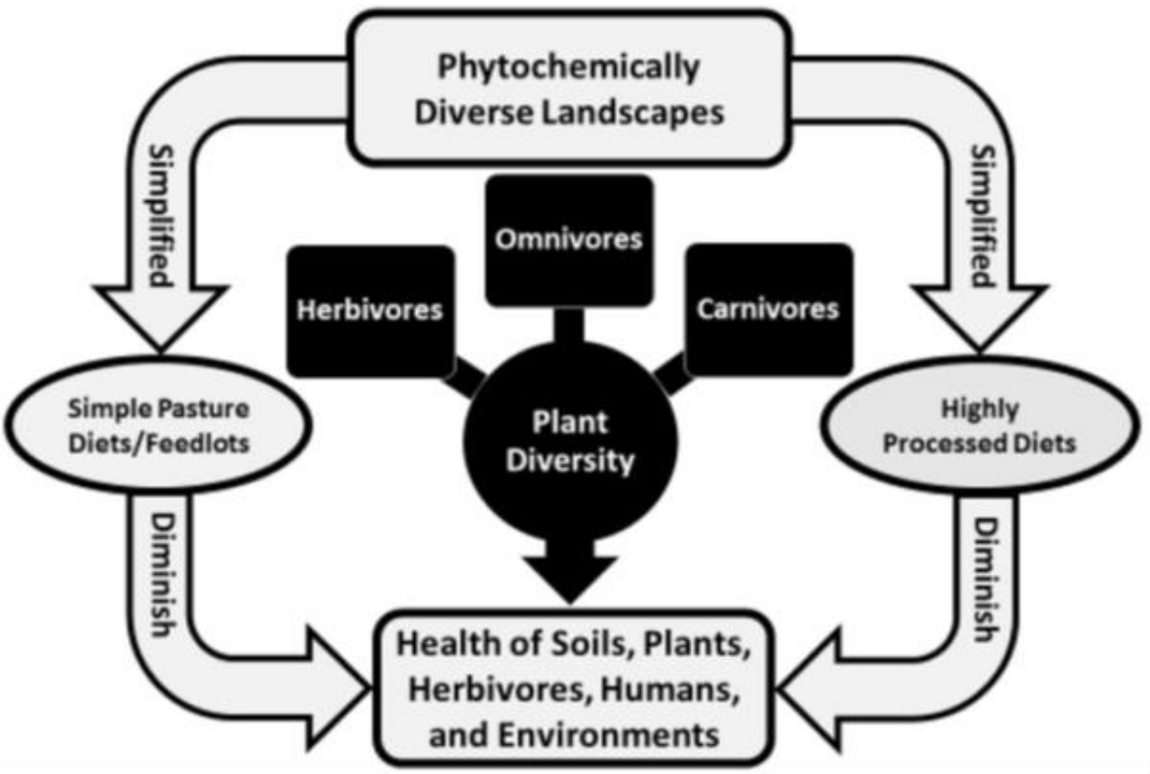

Figure 1. The health of life in soils, plants, herbivores, humans, and environments (land, water, and air) is tied to plant diversity – phytochemical richness – across landscapes. Reproduced from Provenza et al. 2019 under Creative Commons Attribution 4.0 International Licence (http://creativecommons.org/licenses/by/4.0/).

The specific relevance of nutrient density in terms of human health does depend on how it is measured. In order to calculate nutrient density, it is necessary to decide which nutrients in which amounts are the most important to health. There are recommended dietary intakes for nutrients that can be used to assess if a nutrient is present in sufficient amounts to be beneficial, although these are only put in the context of nutrient deficiencies and greater concentrations of nutrients may be needed for disease prevention (National Health and Medical Research Council and New Zealand Ministry of

Health 2006). This is also complicated in that health benefits are different for each nutrient and any one algorithm used to try to quantify healthfulness can be misleading. We also do not fully understand all the compounds in foods that may deliver health benefits, particularly when presented in different combinations.

It has been highlighted by researchers at Tufts University that different foods have different nutritional strengths, so it may not be possible to rank one as more healthful than the other (https://www.nutritionletter.tufts.edu/healthy-eating/the-pros-and-cons-of-nutrientdensity/). For example, “kale is an excellent source of a number of vitamins and phytochemicals, but salmon is rich in healthy fats, so it’s not possible to say one of these foods is better for our health than the other”. Another drawback to rankings is that choosing only highly ranked foods limits the variety of foods (and hence nutrients) being consumed. Additionally, lower ranked foods may be high in important nutrients or compounds not considered in the calculations.

The following sections discuss some measures used for nutrient density and some of the issues with the use of these.

2.3.3 Common measures of nutrient density

In New Zealand, Food Standards Australia New Zealand (FSANZ) uses an online tool for determining whether health claims can be made for a food using the Nutrient Profiling Scoring Criterion (NPSC; https://www.foodstandards.gov.au/industry/labelling/Pages/Consumer-guide-to-NPSC.aspx). However, this only includes a measure of fruit/vegetable macronutrient content, and not vitamins and minerals (apart from sodium) or other bioactive components. The Nutri-Score Nutrient Profiling system is a five-colour front of pack nutrition label derived from the UK Food Standards Authority (FSA) nutrient profiling system with the score ranging from -15 (high nutritional score) to +40 (poor nutritional score) (Kissock et al. 2022). For each food, the Nutri-Score algorithm allocates up to +10 points individually for energy, saturated fatty acids, total sugar, and sodium while allocating -5 points for protein, dietary fibre, fruit, vegetables, nuts, legumes and walnut/rapeseed/olive oils. The whole-grain content of food, with a minimum cut-point of 25%, was added to the algorithm. The overall Nutri-Score value is the sum of the scores from individual components, which is then divided into five classes of nutritional quality ranging from A (green, mostly healthy) to E (red, least healthy).

One of the most widely used concepts is the Nutrient Rich Food index (NRF), which produces a score that can be applied to individual foods and to total diets (Drewnowski & Fulgoni 2020). This is a family of nutrient profiling models that balance nutrients to encourage against three nutrients to limit (saturated fats, sugars, and sodium), using 100 kcal as the basis of calculation. Various iterations of the score exist, which vary in the number of positive nutrients included, ranging from 6 (NRF6.3) to 21 (NRF21.3; Bianchi et al. 2020). However, even the highest of these is limited compared to the diversity of nutrients and phytochemicals present in plant-based foods. Thus, they do not really capture the true nutritional composition/health benefits of all foods.

Another tool recently published is Food Compass (Mozaffarian et al. 2021). This tool includes a broader range of attributes and domains than previous systems with uniform and transparent principles. Food Compass incorporates macronutrients, vitamins and minerals but also multiple health-related food ingredients, phytochemical contents, specific lipids and processing features. A key difference from some other tools is that Food Compass utilises updated evidence for the health effects of both established and emerging factors.

It has been recognised that increased consumption of ‘powerhouse fruits and vegetables’ (PFV), foods most strongly associated with reduced chronic disease risk, is needed. Di Noia et al. (2014) developed and validated a classification scheme defining PFV as foods providing, on average, 10% or more daily value per 100 kcal of 17 qualifying nutrients. The nutrients were potassium, dietary fibre, protein, calcium, iron, thiamin, riboflavin, niacin, folate, zinc, and vitamins A, B6, B12, C, D, E, and K.

The number and type of nutrients included in published nutritional indices varies from six to 22 qualifying, and up to three disqualifying nutrients in NRF indices, and up to 27 qualifying and six disqualifying nutrients in other indices (Green et al. 2023). The question also arises as to whether changes in growing practices resulting in changes in nutrient or phytochemical composition translate to changes in the score in any of these nutrient profiling scoring systems. These tools may easily discriminate a carrot and a chocolate bar in terms of healthiness, but may not capture more subtle differences in composition in a single crop due to different growing practices.

2.3.4 Can Brix be used to measure nutrient density?

Brix is a unit of measure that has traditionally been used in the wine, sugar, fruit, and honey industries to estimate the sugar (sucrose) or water-soluble content, but it does have limitations for wider use, such as for forage crops (Lemus & White 2014). It has been suggested that Brix can be used as a measure of nutrient density, especially in the regenerative agriculture community (e.g. https://koanga.org.nz/how-to-use-a-refractometer/). However, there is no science behind this.

The Brix level measures the sum of all the solids in a sample and this includes sugar, carbohydrates, amino acids, vitamins, minerals and phytochemicals. The relative impact of any one chemical on the final reading depends on the concentration of that chemical in the sample. In fruits, such as apple and grapes, most of the solutes are sugars. However, in other plant tissues such as leaves the composition is more diverse. Many of the chemicals important to our health exist in low concentrations, so changes in their concentration have little or no impact on the final Brix reading. For example, vitamins and minerals are present in very small amounts (milligrams or even micrograms) compared to sugars, which are present in gram quantities. This means that even if growing conditions result in a change in concentration of vitamins and/or minerals, this would not result in a significant change in the Brix reading. For example, a study with lettuce showed significant differences in calcium concentrations but there was no significant relationship between calcium and °Brix (Meagy et al. 2013).

Many genetic and management factors interact to influence crop Brix levels and this can be independent of factors influencing nutritional composition. Similar varieties and management (e.g. fertility, irrigation) will not always result in similar Brix values (Kleinhenz & Bumgarner 2013). Brix values will also vary with other factors, such as year, season and environment. Other factors also influence Brix readings including:

- The method of extracting sap
- Time of day - it is generally lowest at dawn and highest after midday (nutrient concentrations do not change that rapidly!)
- Atmospheric pressure - Brix readings will drop with the onset of a storm when air pressure falls.

Thus, there is no solid scientific evidence that Brix values alone can be used to measure a food's nutrient density.

2.3.5 The Bionutrient Quality Index (BQI)

The Bionutrient Institute (BI) team is a global collection of scientists, technicians, engineers, organisers and others working toward their collective goal to define nutrient density (https://www.bionutrientinstitute.org/). They have been surveying the food supply and analysing crops to gain a deeper understanding of the correlation of management practices to nutrition and quality. However, the current data is not in the peer-reviewed scientific literature and it is limited in what it encompasses (compare to the lists of nutrients in Appendices 1 and 2). The current datasets collected are very narrow in relation to the broader spectrum of nutrients and phytochemicals in food that are important for human health. The Bionutrient Quality Index (BQI; The Bionutrient Institute 2024) includes:

- Total antioxidant content by the FRAP (ferric ion reducing antioxidant power) assay
- Total polyphenol content by Folin-Ciocalteu (F-C) method
- Total protein (for relevant crops)
- Selected minerals: magnesium (Mg), sulphur (S), potassium (K), calcium (Ca), iron (Fe), zinc (Zn).

With regards antioxidant activity measures in vitro, these are of questionable value in relation to human health and a single assay cannot adequately reflect the different antioxidant mechanisms that take place in the human body (Kotha et al. 2022; Munteanu & Apetrei 2021). In addition, antioxidant activity is only one possible mechanism of action of nutrients and phytochemicals (Stevenson & Hurst 2007; Traka & Mithen 2011).

The F-C method for total phenolics is really another antioxidant assay (the fundamental mechanism is a redox reaction) and is not totally specific to phenolics as other compounds can interfere, such as vitamin C, which results in overestimation (Huang et al 2005; Pérez et al. 2023). What is also more important is the presence of specific phenolics as different phenolic compounds have different mechanisms of action/health benefits (Meskin et al. 2004; Rathod et al. 2023; Stevenson & Hurst 2007).

The minerals included in the BQI are restricted to six chosen ones and some are of little significance for most crops. For example, calcium and zinc are low in most fruit and vegetables, so even increasing the concentrations multiple fold does not reach nutritional significance. The index is missing other minerals and does not include any vitamins, which are critical for human health. Current BQI data do show large variations within a crop. There may be multiple reasons for this such as plant variety and growing practices. Without having access to all the metadata, it is not possible to fully interpret the data the institute has published in the reports available via its website (https://www.bionutrientinstitute.org/).

The BI has also developed a ‘Bionutrient Meter’. The BI website states: “By modelling the light bouncing off crop samples against lab derived values of antioxidants and polyphenols, the bionutrient meter can now be used to estimate nutrient density values.” However, it is unclear what this encompasses but appears currently to be linked just to antioxidants, polyphenols and BQI. There is only a single peer-reviewed paper on validation of the bionutrient meter/Reflectometer for phytochemicals (Rosier et al. (2024). The authors state that the results suggest the Reflectometer provides an accurate accounting of phytochemical content within evaluated crops. It should be noted though that by phytochemicals, they are referring to polyphenols (and antioxidant activity). However, it is not possible to fully assess the validity of data for wider application. It is unlikely that such a meter at present can be a comprehensive nutrient density measure including all those components important for health. There are still large gaps in the science and insufficient validation of such a tool for it yet to be seen as comprehensive across different foods.

2.3.6 Chlorophyll

It has been reported that chlorophyll content is an indicator of plants having a higher nutrient content (e.g. California Bioresources Alliance 2017). There is a relationship between rubisco, chlorophyll and plant nitrogen (N) that has been demonstrated in many plants (e.g. Maekawa & Kokubun 2005). Chlorophyl is also an indicator of N status and correlates with plant photosynthetic capability, which then drives plant carbohydrate concentration. However, carbohydrates and nitrogen (hence protein) are not of such significance in many crops and nutrient density. Kalaji et al. (2018) report that differences in soil nutrient content significantly affect the photochemical process of photosynthesis, thereby playing a crucial role in plants' growth and development. Photosynthetic rates may also be important, as plants rapidly release photo-assimilated carbon to the soil via direct root exudation and associated mycorrhizal fungi, resulting in improved nutrient availability for the plant (Kaiser et al. 2015). There is a lack of information in the literature linking chlorophyll concentrations to nutrient density measures. It is likely that the situation is complex and will depend on a raft of factors, including the plant species and part. Different plant leaves while having similar colour (and presumably chlorophyll content) and very different nutrient contents, both qualitatively and quantitatively. Hence chlorophyll content cannot reflect differences in specific nutrients whose synthesis is impacted by a range of other factors.

The relationship between chlorophyll and phytochemical concentrations in a plant is also unclear. For this group of compounds, it may be even more complex because of the diversity of compounds present in different crops (thousands of them). In addition, some phytochemicals, such as the carotenoids, can act as accessory pigments in photosynthesis and can absorb and dissipate excess light energy as well as functioning as antioxidants (McElroy & Kopsell 2009).

Thus, in conclusion the validity of chlorophyll as a marker of nutrient density is highly questionable.

2.3.7 What nutrient density measure should be used for future studies?

There are various different measures/tools that have been used to measure/quantify nutrient density. However, the relevance of any particular nutrient density measure in terms of an impact on human health depends on several things:

- Which components are included (nutrients and phytochemicals)
- How those nutrients are expressed, e.g. per 100 g, per serve, per 100 kcal
- Putting the data in the context in of dietary requirements
- If comparing at a food, meal or diet level.

Nutrient density measures are probably more relevant at a dietary level than for an individual food but also depend on the purpose of using such a measure.

No existing published nutrient density tool is probably appropriate for the study of impacts of growing practices on nutrient and phytochemical composition. This is because they are limited in which nutrients and phytochemicals are included and may not have sufficient granularity to distinguish changes in particular subsets of nutrients. Also to quantify all the components would be expensive and unnecessary (e.g. many nutrients in a single crop would be below concentrations to be of dietary significance). It is probably best to develop a subset of nutrients and phytochemicals to measure based on their presence at/or near dietary significance in the target crops. For example, in an apple the key nutrients of dietary significance are vitamin C and dietary fibre but in a carrot are dietary fibre and vitamin A (beta-carotene). The specifics of what should be included will depend on the questions being asked in any particular study.

3 The impacts of different growing systems on nutrient density and phytochemical composition

This section of the review is focused on the following questions:

- *Is there a difference, and if so what is the difference, in the nutrient and phytochemical content of foods grown using biodynamic methods compared with organic and conventional?*
- *Which compounds are influenced to a greater degree by growing practice (micronutrients, macronutrients, phytochemicals)?*
- *What crops respond best to biodynamics with respect to nutrient content?*

It is important to note that although the different production systems may contribute to the postharvest quality and physio-chemical compositions of produce (Mditshwa et al. 2017), there are other considerations to account for. There are many other factors that can influence the quality and composition of produce beyond the growing practices, either directly or indirectly and some may intersect with the growing practices, making it difficult to directly identify reasons behind differences in composition and sensory characteristics. Factors include genotype, soil properties (pH, available nutrients, texture, organic matter content and soil–water relationships), climate/environment (e.g. temperature, rainfall, light, elevation) and presence/absence of stressors (including predation and disease load) as well as postharvest handling and storage (Dangour et al. 2009; Hornick 1992, 2005; Montgomery & Bikle 2021).

As discussed in Lister et al. (2021), there have been multiple studies across several countries, suggesting that the nutrient density, and specifically the mineral content, of some foods has fallen in the last 50–70 years (Bhardwaj et al. 2024; Davis et al. 2004; Fan et al. 2008; Mayer 1997; Mayer et al. 2022; Thomas 2003, 2007). However, the exact reasons behind these apparent declines are debated (e.g. Marles 2017). Differences could be due to a “dilution effect” (impact of dry matter and yield differences), changes in methodology, sampling differences, changes in the food system, changes in the varieties grown, or changes in agricultural practice. Other research has documented the declining nutrient value in some staple crops may be the result of climate change and elevated atmospheric carbon dioxide (Bhardwaj et al. 2024). These can affect the availability and quantity of nutrients in soil, decrease nutrient uptake by crops and thus reduce protein and mineral nutrient concentrations.

3.1 Compositional differences in foods grown using biodynamic growing practices

There have been two systematic reviews examining the effect of biodynamic farming on nutrient and phytochemical concentrations compared to conventional and traditional organic agriculture (Brock et al. 2019; Santoni et al. 2022). These reviews suggest that biodynamic produce is sometimes higher in phenolics (e.g. flavonoids) and antioxidant activity than its conventional counterpart. The following sections cover studies on specific crops.

3.1.1 Lettuce

Biodynamic Batavia lettuce had a higher concentration of polyphenols, particularly flavonoids, than conventional lettuce under the same conditions of climate, temperature, water stress and plant material (Heimler et al. 2012). For the conventional plots, the amount of mineral fertilisation corresponded to 125 kg ha^{-1} of nitrogen (N), 134 kg ha^{-1} of phosphorus (P) and 14 kg ha^{-1} of potassium (K). Composted manure was spread over the organic and biodynamic plots at the rate of 12.5 t ha^{-1}, the manure supplied 125 kg N ha^{-1} and contained 0.3% P and 0.8% K on a dry weight basis. The biodynamic plots also had field preparation 500 (fresh cow manure buried in cow horns in fertile soil for autumn and winter) and field preparation 501 (made by grinding quartz crystals (silicon oxide) to a fine powder. It is mixed to a paste with water and inserted into a cow horn and buried to spring and summer months and dug up in autumn. It is used at a rate of 2.5 g to 40 L water) (Biodynamics New Zealand 2023).

Polyphenols measured as gallic acid were significantly higher by biodynamic farming (185 mg/100 g) than conventional farming (136 mg/100 g) but similar to organic farming (174 mg/100 g). Flavonoids were lower in conventionally farmed lettuces (109 mg/100 g) than organic or biodynamic farmed lettuces (123 and 139 mg/100 g), but only biodynamically farmed lettuces were significantly higher than conventional (Heimler et al. 2012).

3.1.2 Red beet

Red beet from biodynamic plots farmed under similar conditions had higher total phenolic content and antioxidant activity than from conventional crops (Santoni et al. 2022). The biodynamic farming was according to Demeter International Production Standards and the European Commission Regulation on Organic Farming. The conventional farming was according to the Slovene Agriculture Act and good agricultural practice and organic farming according to the European Regulation on Organic Farming. The conventional farming used traditional N, P, K fertiliser, the organic farming 21,450 kg/ha of cattle manure, and biodynamic farming 18000 kg/ha of composted cattle manure with BD preparations 502–507 added. Total phenolic content ranged from 511 mg GAE/100 g in conventional samples to 677 mg GAE/100 g in biodynamically grown samples. Antioxidant activity ranged from 82 µmol TE/100 g fresh weight in conventionally grown beets to 127 µmol TE/100 g in biodynamically grown samples (Bavec et al. 2010a).

3.1.3 Strawberries

The content of phenolic compounds, flavonoids and antioxidant activity was significantly higher in strawberries from biodynamic farming as compared to conventional (Santoni et al. 2022). Biodynamic and conventional strawberries were grown in southern Lazio (Latina, Italy) in the same pedoclimatic area, biodynamic strawberries were grown using compost and horn as soil supplements. Compared to conventional strawberries, biodynamically grown strawberries had a significantly greater content of ascorbic acid (62 vs 46 mg/100 g), pelargonidin-3-glucoside (39 vs 25mg/100 g), cyanidin-3-glucoside (0.005 vs 0.02 mg/100 g, ellagic acid (53 vs 38 mg/100 g), quercetin (0.17 vs 0.12 mg/100 g) and kaempferol (1.99 vs 1.26 mg/100 g) (D'Evoli et al. 2010).

3.1.4 Mangoes

Mangoes were collected from three types of farming practices (biodynamic, organic, and conventional) in the area of Chapada Diamantina, Piata, Brazil and at three different maturation stages (Maciel et al.

2011). The organic mangoes contained the highest concentrations of phenolic compounds at all maturation stages, followed by the biodynamic with the conventionally grown mangoes being lower for all parameters evaluated. There were differences between the patterns of accumulation with the biodynamic mangoes having the highest antioxidant activity in mature-green and ripe fruits, while the organically grown had the highest antioxidant activity in unripe fruits.

3.1.5 Grapes

A study was initiated in 1996 on a 4.9 ha commercial Merlot vineyard near Ukiah, California (Reeve 2005). The two treatments received identical soil and vine practices, except that the biodynamic preparations were only applied to the biodynamic plots. The biodynamically treated wine grapes had higher total phenolics and total anthocyanins than the organic grapes in 2003 but not in years 2000-2002. However, no comparison was done with conventionally grown grapes.

Döring et al. (2015) assessed the grape quality of three farming systems, integrated, organic and biodynamic. The field experiment was conducted in Geisenheim on a 0.8 ha site that was planted in 1991. The varieties used were *Vitis vinifera* L. cv. Riesling, clone Gm 198-30, grafted on *Vitis berlanieri* Planch. X *Vitis riparia* Michx v=cv. SO4 and *Vitis riparia* Michx x *Vitis cinerea* Englem. Cv. Borner rootstock respectively. The integrated treatment was managed according to the code of good practice. Organic and biodynamic plots were managed according to Regulation (EC) No 834/2007 and Regulation (EC) No 889/2008 and according to ECOVIN- and Demeter-Standards, respectively. Both organic and biodynamic treatments received identical soil and vine management practices except that biodynamic preparations were only applied to the biodynamic plots. The biodynamic treatment showed a significantly higher content of primary amino acids in healthy berries during maturation compared to the integrated treatment (although amino acids are not particularly high).

3.1.6 Potatoes

A series of papers report on the impacts of biodynamic preparations on potatoes. In the first, biodynamic (BD) and conventional field experiments were carried out during two successive growing seasons in 2013 and 2014 on an organic farm in the Prienai district of Lithuania (Jariene et al. 2017). Three coloured-flesh potato cultivars were used: ‘Vitelotte’ and ‘Blue Congo’ with purple flesh and ‘Red Emmalie’ with red flesh. Potatoes were grown using traditional cultivation methods: they were planted in May and harvested in September. Potatoes were fertilised with plant compost (30 t ha^{-1}). The chemical composition of the plant compost was as follows: concentrations of N 4.3 g kg^{-1}, available P 1.068 g kg^{-1}, available K 0.807 g kg^{-1} and pH_{KCl} 6.69. In both years, a two-factor experiment was performed: factor A – three potato cultivars (‘Vitelotte’, ‘Blue Congo’ and ‘Red Emmalie’); factor B – BD preparations 500 and 501 used for field spraying. Four treatments were included to evaluate the effectiveness of BD preparations: (1) Control (without BD preparations); (2) BD 500 (the soil was sprayed two weeks before planting with a 1% solution); (3) BD 501 (early in the morning potato leaves were sprayed with a 0.5% solution twice (at the VIII and IX stages of organogenesis); (4) A combination of two preparations (BD 500 + 501) (two weeks before planting the soil was sprayed with a 1% solution of BD preparation 500 and then early in the morning potato leaves were sprayed with a 0.5% solution of BD preparation 501 twice (at the VIII and IX stages of organogenesis)) (Biodynamic Association Certification). BD preparations 500 and 501 were purchased from a Demeter certified farm in Germany. It was shown that when sprayed with BD preparation 501, the concentration of total phenolic compounds in the tubers of cultivars ‘Blue Congo’ and ‘Red Emmalie’ was significantly higher, 20.1 and 5.4%, respectively; anthocyanins were 59.8 and 10.4% higher, respectively (Jariene et al. 2017). The use of both preparations (500 and 501) had significant effects on anthocyanins accumulation in the tubers of 'Blue Congo' and 'Vitelotte'. However, preparation 500 had the tendency to reduce the concentrations of antioxidant compounds and antioxidant activity in tubers of all potato cultivars. The cultivar was a dominant factor affecting the phenolic antioxidants and the highest concentrations of phenolic compounds, anthocyanins and phenolic acids and the highest antioxidant activity found in the tubers of 'Vitelotte'.

In the second paper, trials included five cultivars of potato with different flesh colours: dark purple ('Violetta'), light purple ('Salad Blue'), red ('Red Emmalie'), yellow ('Laura'), and white ('Tornado'). Potatoes were grown in 2018–2019 at a farm in the Širvintos district of Lithuania. In the conventional farming system, a mix of universal complex fertilisers were used while in the organic and biodynamic farming systems, potatoes were grown in accordance with the IFOAM (International Federation of Organic Agriculture Movements) and Demeter Biodynamic standards respectively. In terms of minerals, the organic and biodynamic potatoes (using preparations 500 and 501) contained significantly more potassium, phosphorus and calcium than conventional potatoes. The organic potatoes had significantly higher contents of magnesium, iron, manganese, zinc and boron than both biodynamic and conventional potatoes (Vaitkeviciene et al. 2020a).

In a third paper, the same five potato cultivars were studied as above and in the same location and practices but in 2017–18 (Vaitkeviciene et al. 2020b). Higher concentrations of polyphenols, phenolic acid, chlorogenic acid, p-coumaric acid and caffeic acid were found in biodynamic and organic samples compared to the conventional potatoes. Organically and biodynamically produced potatoes were significantly higher in flavonoids and anthocyanins. The highest concentrations of carotenoids, including beta-carotene, were in biodynamic potatoes.

3.1.7 Cabbage

Four farming systems were compared, conventional, integrated, organic and biodynamic for white cabbage grown in the northeast of Slovenia (Bavec et al. 2010b). Biodynamic standards were according to Demeter International 2019. Biodynamic cabbage contained more ascorbic acid (vitamin C) than organic cabbage or that produced from an integrated farming system. Potassium concentration was significantly higher in fresh cabbage grown in the conventional system than in the other systems. Untrained evaluators evaluated colour, odour, taste, and overall acceptability) using a nine-point hedonic scale. According to the overall acceptability, samples were ranked control = integrated = organic > conventional = biodynamic.

3.1.8 Tomatoes

D'Evoli et al. (2016) studied tomatoes grown by conventional, organic and biodynamic practices. The biodynamic cultivation was performed using two types of manuring: a) biodynamic with treatments (compost, 500,501 and green manure; b) biodynamic without treatments, only compost and green manure (multifloreal) was used. Differences in nutritional quality and phenolic acid content were related to year of production rather than type of production system.

3.1.9 Rapeseed

Effects of integrated, organic and biodynamic farming on rapeseed were investigated (Turinek et al. 2017). The farming systems differed primarily in plant protection and fertilisation strategies, and the legislative requirements and standards of integrated, organic and biodynamic farming. Biodynamic standards were according to Demeter International 2019. Fertilisation in the integrated farming system was performed with mineral fertilisers. Composted cattle manure was applied in the amount of 1.4 livestock units per hectare on the organic farming system. The same equivalent of composted cattle manure with the addition of biodynamic preparation (BD 502-BD507) was used in the biodynamic system. The biodynamic and organic farming systems had increased oleic fatty acid and oil content in comparison to the integrated system. The integrated system had higher concentrations of protein and linolenic, gadoleic and hexadecadienoic fatty acids.

3.1.10 Chicory

Heimler et al. (2009) investigated the polyphenol content and antiradical activity of chicory from biodynamic and conventional farming. Total phenolics were not significantly different between biodynamic and conventional farming – during the first sampling period phenolics were higher by conventional farming, but not significantly. Total flavonoids were similar by the two farming methods. Antiradical activity was similar by biodynamic and conventional farming methods during the first sampling but lower by biodynamic methods during the second sampling (33.81 vs 48.60 mg sample fresh weight/mg DPPH). In terms of the methods, *Cichorium intybus* L., cv. 'Spadona' was cultivated under biodynamic and conventional production systems in replicated plots in the experimental orchard of the Biodynamic Association of Tuscany, located in Florence, Italy. The design was composed of three blocks, each containing a conventional and biodynamic plot. In November 2006, six plants of chicory were planted in each plot and were treated with preparation 500 (biodynamic production) and Nitrophoska Gold® (5 g each plant, conventional production); the main ingredient of preparation 500 is cow (*Bos taurus*) manure and it is used as field spray. The first sampling was taken in May 2007. After sampling, weeds were removed and a further treatment with preparation 500 and Nitrophoska Gold was carried out. The final sampling was performed in June 2007 (Heimler et al. 2009).

3.1.11 Pumpkins

An investigation on the effect of horn manure and horn silica was carried out on an organic farm in Kaunas district, Lithuania from 2012 to 2014. The three trial years were carried out each year on a new field of the organically managed farm. The respective trial area with pumpkin was fertilised in the trial year with 30 t ha^{-1} of plant compost (pH_{KCl} 6.97, available P_2O_5 1932 mg kg^{-1}, and mineral N 53 mg kg^{-1}, the compost was 2 years old). In a two-factorial field trial, different cultivars of winter squash and the use of biodynamic preparations were examined in four field replications as block design. Three giant pumpkin (*Cucurbita maxima* Duchesne) cultivars 'Justynka F1', 'Karowita' and 'Amazonka' developed by breeders at the Warsaw University of Life Sciences in Poland were grown. The effect of biodynamic preparations was examined by four variants. Horn manure (HM: fermented manure) and horn silica (HS: ground silica SiO_2) were each tested individually and in combination. In the control variant, no treatment was applied.

Horn manure and horn silica application significantly increased contents of total carotenoids, single carotenoids (lutein+zeaxanthin, lycopene, β-carotene) and antioxidants (catechins, total phenols, leuco-anthocyanins) (Juknevičienė et al. 2019; 2021). Horn manure without horn silica reduced antioxidant concentration, as observed in potatoes (Jariene et al. 2017).

3.1.12 Apples

Masi et al. (2017) was able to differentiate the polyphenol content of biodynamic and conventional apples but it was not possible to differentiate the samples regarding the volatile compounds. Unexpectedly, the total flavanols in the apple skin were higher in the conventional samples (1129 µg/g and 1190 µg/g in the conventional versus 763 µg/g in the biodynamic samples). In the apple pulp, the conventional A and biodynamic samples were similar (4.6 vs 5.1 µg/g), whereas conventional B was lower (2.8 vs 5.1 µg/g). 'Golden Delicious' apples (*Malus domestica*, Bork.) grown in three commercial orchards, two located in the north of Italy (Trentino Alto Adige, "A"), and one in central Italy, (Tuscany, "B"). A minimum of 40 fruits, with similar and without visible external damage, were hand-picked from at least 15 healthy trees for each orchard. The conventional agronomic management was applied in one orchard in Trentino Alto Adige (CON-A) and in Tuscany (CON-B), while the third orchard (BIO-A) was managed following biodynamic protocols. The Tuscan conventional orchard (2857 plants/ha; 40 t/ha fruit yield) was planted in 2007 on a clay loam soil with a SE-NW field exposure. The two orchards from Trentino Alto Adige were both established in 1998 on adjacent areas, thus under very similar soil (rocky soil texture) and environmental conditions. The planting density was 2032 and 3333 trees/ha, with an average yield of 55 and 85 t/ha of apples, for the biodynamic and conventional orchard, respectively. The biodynamic orchard was run according to the indications of Rudolf Steiner, and was protected from external abiotic and biotic contaminations by living hedges. The soil fertility was maintained exclusively with periodical sowing of mixed herbaceous plants (especially belonging to the families of Leguminosae and Cruciferae), and with distribution of organic matter (cow manure), produced internally, and composted according to biodynamic indications. Pest management was performed mainly using horn-based biodynamic preparations, or with organic products.

3.1.13 Grains

Campbell et al. (1991) reported that studies have been unable to find significant differences in nutrients between organically and conventionally grown grains. No significant differences were found in protein, fat, carbohydrates, minerals (micro and macro), trace elements, pesticide residues, and heavy metals for grains grown under the same climate and soil conditions.

3.2 Compositional differences in foods grown using organic versus conventional systems

Is there a difference between the nutrient and phytochemical content of foods grown using organic and conventional systems?

There is significant body of literature comparing organic crops to conventional crops in relation to vitamins, minerals and phytochemicals, where the organic crops are not biodynamic. However, the quality of some of these studies is questionable and findings have been inconsistent. This is both looking across different crops or even within a crop examining different studies.

Baranski et al. (2014) reviewed 343 peer-reviewed publications that compared organic and conventionally grown crop-based foods. Concentrations of antioxidants were found to be substantially higher in organic crops. The concentrations of flavonoids and phenolic acids were substantially higher in organic crops. The frequency of pesticide residue was found to be four times higher in conventional crops. Conventional crops also had higher concentrations of up to 48% of cadmium. Another group found that phytochemicals such as phenolics were 10 to 50% higher in organic vegetables than in conventional vegetables (Brandt & Molgaard 2001). Rembialkowska (2007) reported on the content of desirable components in organic crops relative to those in conventional crops. Organic crops contained fewer nitrates, nitrites and pesticide residues but more vitamin C and phenolic compounds than conventional crops.

Bernacchia et al. (2016) concluded that in almost every study claiming large nutritional differences between organically and conventionally grown produce, the experiments failed to control similar environmental inputs that affect plant and fruit development, yield and quality. When this lack of methodological rigour was overcome by the application of a systematic review, significantly higher concentrations of antioxidant compounds and lower cadmium concentrations in organic food products were demonstrated.

Montgomery et al. (2022) compared soil health and nutrient density in regenerative (organic) and conventional farming. It was a very well-run study with paired farms across the United States. Averaged across nine farm pairings, the regenerative farm crops had 34% more vitamin K,15% more vitamin E, 14% more vitamin B1 and 17% more vitamin B2. The crops from the regenerative farms also had 15% more carotenoids, 20% more total phenolics and 22% more total phytosterols. Finally regenerative crops had 11% more calcium, 16% more P and 27% more copper. Unfortunately, from the study we can only draw conclusions that in some cases organically grown crops can have higher nutrient density compared to conventional crops (but only for some selected components) – there was no separation into crops grown using biodynamic practices.

There is some evidence that organically grown produce does have higher concentrations of some nutrients (e.g. vitamin C). There do appear to be significant differences in the phytochemical content of organic and conventional crops. Like biodynamics, there is evidence that organic production practices can result in higher concentrations of phenolics. This may be a consequence of greater plant stress, greater soil microbial activity and lower soil N. In addition, organically grown produce typically has lower nitrate and pesticide concentrations. However, making claims of organic produce holding higher nutritional value and health benefits can be difficult to authenticate because of the wide variety of production systems and overlap in management practices.

3.3 What crops respond best to biodynamics with respect to nutrient content?

To make a sound recommendation as to which crops respond best to biodynamics with respect to nutrient content, it would be desirable to have several studies on the same crop that consistently found a greater nutrient content. However, there have been few studies on any crop that compare the nutrient content of biodynamic produce with that grown using other systems (Section 3.1), let alone several studies on the same crop. The Bionutrient Institute has identified fruits and vegetables, and beef in their research as responding well to biodynamic practices (The Bionutrient Institute 2024). However, these data are not in the peer-reviewed literature and it is hard to fully interpret the results from the website without all the metadata and specific details. In addition, the nutrients measured are very limited. Therefore, this section is a “best guess” based on extremely limited data.

Based on the limited number of studies in the scientific literature, which were reviewed in Section 2.2, crops that responded best to biodynamics are summarised in Table 2. Crops that showed a large response compared with conventional farming included red beet, lettuce and strawberries. Crops that did not show higher nutrient content under biodynamic production than conventional and/or organic systems were tomatoes, chicory, apples and grains (Section 2.2). In general, crop responses to biodynamics were greater compared to conventional farming than compared to organic farming (Table 2). This is probably because biodynamic farming has more in common with organic farming, than with conventional farming. In some studies, the only difference between the biodynamic and organic systems being compared was the use of the biodynamic preparations.

Table 2. Crops that responded best to biodynamics in terms of nutrient content, based on the limited number of studies in the scientific literature. NS=not statistically significant at P<0.05.

Crop	Nutrient	% increase c.f. conventional	% increase c.f. organic	Reference	Comments
Red beet	Total phenols	32	NS	Bavec et al. (2010a)	
	Antioxidant activity	55	NS	Bavec et al. (2010a)	
Lettuce	Polyphenols	36	NS	Heimler et al. (2012)	
	Flavonoids	28	NS	Heimler et al. (2012)	
Strawberries	Vitamin C	35	-	D'Evoli et al. (2010)	
	Flavanols	NS-60	-	D'Evoli et al. (2010)	No difference in myricetin, but significant increases for quercetin and kaempferol
	Antioxidant activity	26	-	D'Evoli et al. 2010	In crude extract
Grapes	α-amino acid content	NS-51	NS	Döring et al. (2015)	Only significant in 3rd year of trial
Grapes	Brix	-	1	Reeve (2005)	Anthocyanins and phenols were significantly higher at p<0.1
Cabbage	Vitamin C	NS	33	Bavec et al. (2010b)	52% more than integrated farming
Pumpkin	Total carotenoids	-	9-17	Juknevičienė et al. (2021)	Depending on cultivar
	Catechins	-	7	Juknevičienė et al. (2021)	In 1 of 3 cultivars
	Phenolics		25	Juknevičienė et al. (2021)	In 1 of 3 cultivars
Potatoes	Total anthocyanins	-	NS–21%	Jariene et al. (2017)	Significant in 2 out of 3 cultivars

There is, however, a much wider amount of data available that compares the nutrient content of organic systems with conventional. Given that the nutrient content of biodynamically produced food is more closely aligned to organically produced food than conventionally produced food in three-way studies (Table 2), another approach is to identify crops that respond well under organics and assume they will likely respond well in a biodynamic system. The conclusions were that organic crops often contain higher concentrations of phenolics and flavonoids, with lower concentrations of pesticides and cadmium. One obvious crop choice is grapes, where these qualities are highly sought after in wine. This conclusion appears to be already recognised by biodynamic growers, since half of the biodynamic growers in New Zealand grow grapes (Joanne Turner, Demeter New Zealand, pers. comm.).

3.4 Summary

There has been limited study on the effect of biodynamic farming on nutrient and phytochemical concentrations compared to conventional and traditional organic practices. The current reviews suggest that biodynamic and organic practices sometimes result in plants higher in phenolics (e.g. flavonoids) and antioxidant activity than their conventional counterparts. There is a greater body of research comparing organic and conventionally grown crops. In general, there appears to be limited impact of organic practices on macronutrient composition but some evidence of impact on selected micronutrient (vitamin and mineral) concentrations. However, there is more evidence for beneficial impacts in other areas, including more antioxidants such as phenolics, less cadmium and fewer pesticide residues in organically grown crops. However, there is variability from crop to crop and even in some cases between studies on the same crop.

4 Differences in nutrient supply or availability among production systems

4.1 Introduction

If there are differences in mineral nutrients in food among production systems, then it is of interest to know whether they arose from differences in nutrient supply or availability. This section addresses the question:

- *What nutrients are inputted and produced in biodynamic systems, compared to organic and non-organic systems?*

For this section, the word “nutrient” has been interpreted as what is relevant to plant production, since the nutrients that plants require for healthy growth are different to those required by humans. Organic compounds that are essential for human nutrition, such as vitamins, are not essential for plants, so are not considered, although links will be made to the plant content of these where they are influenced by inputs into the production system. The essential plant nutrients considered are the macronutrients: N, P, K, calcium (Ca), magnesium (Mg) and sulphur (S), and the trace elements: iron (Fe), manganese (Mn), boron (B), zinc (Zn), copper (Cu), molybdenum (Mo), nickel (Ni) and chlorine (Cl). These nutrients are supplied via the soil. The supply of nutrients derived from water or the atmosphere: carbon (C), hydrogen (H) and oxygen (O), is not considered to differ with production system, so is not discussed, although soil water-holding capacity may increase in biodynamic or organic systems (Arpana et al. 2014).

Nutrients that are inputted have been interpreted as nutrients that are supplied by the grower; what nutrients are produced has been interpreted as “What nutrients are produced or made more plant-available in the different production systems?” So this section has been divided into two parts, part 1 discusses differences in nutrient supply among the production systems, and part 2 discusses differences in nutrient production or availability among the production systems

4.2 Differences in nutrient supply among production systems

Conventional systems are characterised by the predominant use of synthetic fertilisers (although some natural and organic nutrient sources are also used) whereas both biodynamic and organic systems use no synthetic fertilisers. The main difference between biodynamic and organic systems, in terms of nutrient addition, are the nine different preparations (Preparations 500 to 508) commonly used for preparing fields and making composts with some of these Preparations. These preparations (Table 3) add little to the soil in terms of kilograms of nutrients per hectare, so in theory, biodynamic and organic systems may be expected to supply the same amounts of nutrients. In practice, behaviour may be quite different. For example, Zikeli et al. (2017) studied non-conventional vegetable production in greenhouses and noted that fertiliser strategies in Demeter-certified farms used high to very high amounts of base dressings (solid and liquid farmyard manure, composts, incorporated green manure), while the Bioland (organic) members focused strongly on nutrient inputs via base and top dressings of complementary commercial fertilisers (horn products, MALTaflor®[2], vinasse and K sulphate). This resulted in Demeter members applying roughly double the amount of N, P and Na, and more than

[2] A blended fertiliser based on malt sprouts from the brewing industry and vinasse from the sugar industry.

triple the amounts of K, calcium and magnesium of Bioland growers. Unfortunately, there is very little information on what nutrients biodynamic growers actually apply, so the remainder of this section largely focuses on comparisons of inputs between organic and conventional farms.

Table 3. The main ingredients and recommended amounts of the biodynamic preparations used on land (Preparations 500-501: Source - Biodynamics New Zealand 2022) or in up to 14 t compost (Preparations 502-507: Source - Reeve et al. 2010).

Preparation	Main ingredient	Use	Application rate	
500	Fresh cow manure	Soil	30-100 g in 30-100L of water per ha	
501	Finely ground quartz	Plant spray	2.5 g per 40 L water	
			Unit volume (cm^3)	**Unit mass (g)**
502	Yarrow blossoms (*Achillea millefolium* L.)	Compost	15	1.1
503	Chamomile blossoms (*Matricata recutita* L.)	Compost	15	3.0
504	Stinging nettle shoots (*Urtica dioica* L.)	Compost	15	4.4
505	Oak bark (*Quercus robur* L.)	Compost	15	3.9
506	Dandelion flowers (*Taraxacum officinale* L.)	Compost	15	4.7
507	Valerian flower extract (*Valeriana officinalis* L.)	Compost	2	1.2

4.2.1 Nitrogen supply

Many reviews state that organic and biodynamic crops often yield 5–58% less than conventionally grown crops (e.g. Aulakh et al. 2022; Nieberg & Schulze Pals 1996; Halberg & Sillebak Kristensen 1997; Berry et al. 2006). There are several possible reasons for this, but one explanation is that the supply of plant-available N in the soil is limiting production (Berensten et al. 1998; Eltun 1996; Tortensson 1998). A large survey of Swedish dairy and arable farms found that conventional farms applied 70% and 40% more N than corresponding organic farms (Wivstad et al. 2023). Nitrogen surpluses on conventional dairy farms were almost double that of organic dairy farms in a Danish study (Dalgaard et al. 1998). Berry et al. (2006) point out that the grain N concentration that coincides with maximum yield in bread wheat is approximately 2.2%. The grain N concentration in conventionally grown bread wheat averaged between 2.2–2.3%, whereas that of organically grown wheat averaged 1.75% (range 1.5–1.9%). Some of the main reasons they give for the lower N concentration are:

- Many certification bodies encourage composting, which reduces the N content of residues by 25-44% (Dewes 1995)
- The low percentage of compost N taken up by the crop receiving the compost (6-22%)
- The generally higher C:N ratios of organic crop residues compared with conventional
- Autumn incorporation of composts resulting in N leaching losses over winter
- The slow mineralisation rate of organic N sources.

Berry et al. (2006) also provided suggestions on how these limitations could be overcome. Regardless of the reasons or solutions, it is sufficient to note that inputs of crop-available N are often lower in organic (and presumably biodynamic) systems than in conventional systems. This lower N supply may potentially impact the protein content and amino acid composition of foods (Granstedt & Kjellenberg 1997; Döring et al. 2015).

The flip-side of these statistics is that conventional growing is more likely to result in excessive N application than organic or biodynamic production (e.g. Wivstad et al. 2023). Excessive N application may cause plants to reduce the production of phytochemicals that protect them against disease and insect attack, e.g. phenolic compounds (Bryson et al. 1997; Brandt et al. 2011), which affects the nutrient composition of food. Similarly, reduced soil N supply increases the production of defensive compounds in plants (Brandt et al. 2011). High soil N supply can reduce the availability of B, K and Cu. High soil concentrations of available P can reduce the uptake of Fe, Ca, K, Cu and Zn. High soil K can reduce the uptake of Mg. Thus, unless care is taken to ensure an adequate balanced supply of all the nutrients, the application of very high concentrations of N, P and K in compound fertilisers can induce plant deficiencies of other essential nutrients (Measures 2018). Excessive N application also increases the risk of nitrate loss to waterways, which is undesirable as nitrate can promote algal growth and high concentrations of nitrate make groundwater unfit for drinking (Bijay-Sing & Craswell 2021).

4.2.2 Phosphorus and potassium supplied in intensive horticultural systems

Intensive horticultural systems require large amounts of plant-available N to feed rapidly growing vegetable crops. As discussed in the previous section, N is commonly limiting plant production on organic properties, despite N budgets showing a surplus of total N is typically applied (Watson et al. 2002). Organic fertiliser options are often imbalanced, having a lower N to P ratio than crops require. The reason why N supply is often low relative to P, despite organic systems being fertilised with plant or animal-based products such as composts and manures, is that approximately one quarter of the N may be lost during the composting (Dewes 1995; Sommer & Dahl 1999; Beck-Friis et al. 2001), whereas almost all the P is retained. This imbalance is exacerbated by the fact that only some of the N is available for uptake by the current crop (Gutser et al. 2005), whereas practically all of the P is available (Schröder et al. 2011). The imbalance of nutrient supply in intensive organic or biodynamic systems has been highlighted in a number of studies (references cited in Möller 2018). Zikeli et al. (2017) assessed the nutrient balance of organic and biodynamic covered vegetable production farms, and noted large excesses of Ca, Mg, Na, P and S were applied, but a deficit of K, relative to what was removed in the harvested crop. The amounts of excess nutrients applied were much greater for the Demeter crops than the organic crops for all nutrients except S, and the deficit of K was much less. It is important to note that these intensive horticultural systems (Zikeli et al. 2017), although Demeter certified, represent a large departure from the ethos of biodynamic farming, with no livestock on the property, and no use of N-fixing crops.

A contributing factor to the low supply of N, and particularly K, in relation to P may occur if not all of the urine is captured and returned with the composted manure to the land. For mammals, almost all of the P in excreted is partitioned into the dung, much of the K into the urine, and the N is split between the dung and the urine (e.g. Gustafson & Olsson 2004). If both the dung and the urine are returned to the plants, then fewer nutrients are lost. However, in animal housing systems where some or most of the urine is able to drain away and the compost is made from this manure, the return of nutrients becomes unbalanced, resulting in the inputs of P, Ca, Mg, S and Na relative to N and K. Trace elements are also partitioned into manure rather than urine in cattle (Gustafson & Olsson 2004). Potassium sulphate may be used in both organic and biodynamic systems, but this further increases the excess of S in the system. This nutrient imbalance is only likely to be seen in intensive systems with a heavy reliance on manure, being less so in low-input production and systems where both urine and dung are returned. In the long-term organic and biodynamic trial at Skilleby, Sweden, Granstedt (2002) concluded that supplementing livestock manure with urine at 20 t/ha (20 kg N/ha) was an effective treatment for regulating harvest yield and protein concentration.

4.2.3 Phosphorus and potassium supplied on less intensive farms

Watson et al. (2002) calculated N, P and K nutrient balances for 88 organic farms from nine different countries. These included a range of farm types; the majority (79%) were dairy farms, 8% were biodynamic (although specific nutrient input data for biodynamic farms were not supplied), only 3% were horticulture. Only four farms imported manure, in contrast to the high reliance on purchased manure in the intensive horticultural systems reported above. All farms studied by Watson et al. (2002) had a positive total N balance (average 83 kg N/ha/y), although much of the N surplus on dairy farms is assumed to be lost by leaching, volatilisation and denitrification (Aarts et al. 1992; Jarvis et al. 1996). Most farms investigated by Watson et al. (2002) had positive nutrient balances for P and K (average 4 and 14 kg/ha/y, respectively). There was a wide range in calculated nutrient balances. Average nutrient balances for German dairy farms were close to zero, being -3 kg/ha (range ±7 kg/ha) for P and 1 kg/ha (range ±14 kg/ha) for K (Haas et al. 2007). In their review on soil nutrient dynamics in organic systems, Friedel & Arakani (2021) note that nutrient budgets were more negative on farms that sold product yet were self-sufficient for feed or that return only small amounts of manure, and more positive on farms that bought more supplementary feed, bedding material, compost or fertiliser. Note that rock phosphate is permitted as sources of P, and K sulphate a K source if there is a demonstrated deficiency (Biodynamic Association 2012). As a consequence of these near-zero nutrient balances for K, and the renunciation of readily available K fertilisers, Friedel & Arakani (2021) conclude that labile (readily plant-available) K fractions in soil are generally at lower concentrations in long-term organic farming than in conventional farming, but see (Tyburski & Sienkiewlcz 2010). Limited data for labile P concentrations in soil showed no overall trend, with Canadian dairy and arable farms (Schneider et al. 2016 and references cited therein) and Polish (Tyburski & Sienkiewlcz 2010) data showing lower P in organic farms, but in more intensive horticulture, data from Australia (Nachimuthu et al. 2012) and the Netherlands (van Diepeningen et al. 2006) showing no difference between organic and conventional farms.

4.2.4 Supply of other nutrients

Biodynamic and organic and cropping systems typically input a much larger amount of organic matter than conventional systems, e.g. compost, manure and green manure (Dubgaard & Sorensen 1988; Reganold et al. 1993; Nelson et al. 2010). In terms of nutrients, these supply both macronutrients nutrients and micronutrients, as opposed to conventional farming that often emphasises applications of N, P and K, since these are the most common nutrients to which crop yield will respond. Hence biodynamic and organic farms may supply higher rates of Mg, S and micronutrients than conventional farms (Maqueda et al. 2011; Kwiatkowski & Harasim 2020).

4.3 Differences in nutrient production or availability among production systems

In terms of nutrient production by the three farming systems, N is the only nutrient that can be produced, which occurs by biological fixation of N_2 gas from the atmosphere. Increases in supply of the other essential plant nutrients must occur either by inputs from the grower (discussed above) or by increasing the plant-availability of nutrients that already exist in the soil, which is discussed in this section. But first we will discuss the production of N.

The fixation of atmospheric N_2 by legumes is key to meeting the N requirements of plants in biodynamic and organic systems, which cannot use chemical fertilisers like conventional systems. Möller (2018) stressed that the use of legumes to fix N was vital to addressing the low N:P ratio on intensive horticultural organic and biodynamic farms that rely on heavily manures, composts and other organic materials to supply N. Granstedt (1992) recommended that legumes should be planted on one-third of the farm to meet the N requirements of biodynamic farms. Therefore, there is typically a greater production of N on biodynamic and organic farms, occurring through N fixation by legumes, compared with those conventional systems that use chemical N fertiliser, where the N production occurs off-farm (Wivstad et al. 2023). No data were found as to whether there were differences in N production from biological N fixation between biodynamic and organic systems.

In terms of differences in the availability of nutrients between farming systems, this may be influenced by the increases in soil organic matter in biodynamic and organic systems (Hepperly et al. 2018) over conventional, and possible differences in the microbial communities. Differences between biodynamic and organic systems are fewer and there are less data. Some studies where differences were found are mentioned here. Higher crop yields, along with higher concentrations of plant-available N and K (Juknevičienė 2015 in Juknevičienė et al. 2019; Vaitkevičienė 2016 in Vaitkevičienė et al. 2019) and P (Juknevičienė 2015 in Juknevičienė et al. 2019; Vaitkevičienė 2016 in Vaitkevičienė et al. 2019) have been measured in soils after the applications of biodynamic preparations compared with control treatments. The application of biodynamic preparations 500 and 501 increased the yield of rice by 15% and the available P in the soil at harvest by 25% compared with unfertilised soil (Valdez and Fernandez 2008). The long-term DOK[3] trial found greater amounts of calcium but less magnesium in biodynamically managed soil compared with the similarly managed organic treatment without these preparations (Mäder et al. 2002).

Possible mechanisms for differences in nutrient availability to plants among the different farming systems are:

- **Mycorrhiza:** Mycorrhizal fungal associations with plant roots assist in the uptake of poorly mobile nutrients in soils such as P, but also help in the uptake of many trace elements, particularly Zn (Lehmann et al. 2014). At higher concentrations of plant-available P in soils, plants reduce root exudate production resulting in less mycorrhizal association (Konecny et al. 2019), resulting in lower mineral uptake (Montgomery & Biklé 2021). Conventional farms may have higher plant-available P concentrations than organic and biodynamic properties (e.g. Schneider et al. 2016, but also see van Diepeningen et al. 2006 and Nachimuthu et al. 2012), which may mean lower mycorrhizae association and lower uptake of minerals such as Zn (Ryan et al. 2004). Mycorrhizal colonisation has repeatedly been found to be higher in organic farming compared with intensive or conventional farming (Friedel & Ardakani 2021). High N fertiliser use also reduces the abundance and diversity of mycorrhizal fungi (Egerton-Warburton & Allen 2000).

- **Effects on the microbial population, which influence the plant-availability of nutrients in compost:** Many studies report enhanced microbial activity in organic and biodynamic systems

[3] The trial compared three farming systems: biodynamic (D), bioorganic (O) and conventional (K; German: konventionell) agriculture. These systems differed both in terms of fertilisation (D: slurry, manure compost, biodynamic preparations; O: slurry, rotted manure; K: slurry, fresh or rotted manure, mineral fertilisers) and plant-protection (D and O: biological; K: chemical-synthetic).

compared with conventional (e.g. Reganold et al. 1993; Condron et al. 2000; Fließbach et al. (2007). This enhanced microbial activity can boost nutrient availability by either increasing nutrient solubilisation or by improving the release of organically bound nutrients into plant-available forms. Differences between biodynamic and organic systems are less commonly reported in the scientific literature. Most of the biodynamic preparations are applied to compost. The two-year study of Carpenter-Boggs et al. (2000a) and five-year study of Rienth et al. (2023) report no difference in the effect of biodynamic or organic composts when added to soil. Several studies have reported higher temperatures in compost receiving biodynamic preparations than those that did not (Wistinghausen 1984; Koepf 1989; Carpenter-Boggs et al. 2000b), although Zaller (2007) did not. Carpenter-Boggs et al. (2000b) report 65% more nitrate in compost prepared with the additions of biodynamic preparations than in compost without these preparations, with similar ammonium concentrations in both composts. Phosphatase, dehydrogenase and protease enzyme activity were greater in biodynamic plots than in organic plots in a 21-year Swiss study (Mäder et al. 2002). Phosphatase and protease enzymes release plant-available P and N from organic matter, respectively. The nine-year study of Zaller & Köpke (2004) shows a lower metabolic quotient in soils receiving biodynamic compost, rather than organic compost. This may indicate that microbial communities are more able to use organic substances for growth rather than maintenance, or that the compost was more mature, with more humified material in the biodynamic compost. There is a need to understand how the addition of such small amounts of material (≤15 cm^3; Table 3) may have significant effects on up to 14 t of compost, which is spread even further when the compost is added to soil.

- **Enhanced root growth via hormonal effects:** Stearn (1976) proposed that the biodynamic preparations may have hormonal effects that stimulate root growth, which may lead to enhanced nutrient uptake of immobile nutrients such as P. Botelho et al. (2016) looked for of isopenthyl adenine, indole-3-acetic acid, and abscisic acid and found that they were below detection limits. Cytokinins were detected in preparation 500, but when factoring in the dilution rate over one hectare, the rates were four to five orders of magnitude lower that those used in commercial practice, causing them to conclude that a hormonal mode of action for biodynamic preparations was unlikely. In contrast, Giannattasio et al. (2013) found that biodynamic preparation 500, diluted to a comparable level to that applied in the field and applied to watercress, contained sufficient auxin-like activity to qualify for use in soil as a biostimulant. Valdez and Fernandez (2008) also measured a 15–60% increase in lowland-rice root biomass (depending on variety) in the treatment that received biodynamic preparations 500 and 501, compared with the control. Both treatments received no compost or fertiliser. Assuming the increase in root biomass resulted in an increase in root surface area, then this is likely to increase nutrient uptake of immobile nutrients such as P. This may indicate possible hormonal effects of these biodynamic preparations. This conflicting evidence and scarcity of information led reviewers Santoni et al. (2022) to conclude that further research is needed concerning this mechanism.

- **Differences in soil organic matter content:** Numerous studies have shown significant increases in soil organic matter in biodynamic and organic compared with conventional systems (e.g. Droogers & Bouma 1996; Granstedt & Kjellenberg 1997; Brock et al. 2012; Montgomery & Biklé 2021). A greater amount of soil organic matter increases the cation exchange capacity of the soil, increasing the soil's ability to hold positively charged nutrients, which includes most trace elements. Boron storage is also increased as soil organic matter concentrations increase, although the effect of compost on B availability to plants may vary

(Dhaliwal et al. 2019). Increases in organic matter generally increase the plant-availability of trace elements (Shuman 1997; Dhaliwal et al. 2019).

4.4 Summary

In summary, there is a wide range of nutrient inputs used in different farming systems and even within the same type of system. Some crude generalisations may be made, which may not be true on any particular farm. In general, biodynamic and organic systems supply lower amounts of plant-available N than conventional systems. The supply of P, Ca, Mg, S and Na in organic, and particularly biodynamic, intensive vegetable production systems may be much greater than plants require, relative to N and K. Note that these intensive vegetable production systems represent a considerable departure from the ethos of biodynamics. Less intensive organic and biodynamic systems show a neutral to positive balance for P and K on average, although there was a wide rage in the data. Balances were negative where no inputs were purchased to replace nutrients exported in produce. The supply of other macro- and trace elements may be greater on biodynamic and organic systems that bring in large amounts of manure or compost, compared with conventional farms that focus on the supply of N, P and K; in other cases no differences in inputs may be expected.

Part two of this question examined differences in nutrient production and availability among farming systems. Regarding nutrient production, N_2 fixation is strictly the only way nutrients are *produced* on-farm. Nitrogen fixation mostly occurs through growing legumes, and this is likely to be greater on biodynamic and organic properties than conventional farms that use N fertilisers. In terms of differences in nutrient availability, increases in organic matter and microbial activity may increase nutrient availability in organic and biodynamic systems compared with conventional systems where this nutrient is not supplied by a fertiliser. There are few studies that compare differences in nutrient availability between biodynamic and organic systems. Of these, some report differences in nutrient availability. This may be a result of a more effective composting process, other authors suggest a hormonal effect, although some disagree. There is a need for further research as to whether there is a difference in nutrient availability between biodynamic and organic systems, and if so, what are the reasons why.

5 Aspects of soil microbiology and health that contribute to plant nutrient density

5.1 Introduction

This section addresses the question:

- *Does the microbial biomass of living soil in biodynamics, organics and conventional growing systems influence the nutrient density of food produced?*

As there is no specific literature that addresses this question directly, answering this question requires inference across a variety of related studies. It should be noted that keyword searches to find reference materials that approach answering the question can introduce confirmation bias, but the overall conclusion is that microbial biomass has an important role to play in building soil health and controlling nutrient flows so it will contribute to plant health, including nutrient density. An alternative framing of the question was also used that specifically referenced biodynamics, this being: *"Is the nutrient density of food influenced by microbial biomass of living soil in biodynamic systems?".*

This section focuses on the impact of biodynamic practices on microbial biomass in soil and nutrition in comparison to other management systems. The general assumption is that healthier soil supports a higher biomass, higher biomass is likely to harbor greater diversity, which leads to more complex ecological relationships, greater biogeochemical functionality (nutrient acquisition and recycling), altered microbial metabolic activity, but most importantly higher throughput and turnover of carbon, carbon storage potential (including via microbial necromass) which in-turn builds soil organic matter (Cotrufo & Lavallee 2022). Soil organic matter is more than just carbon; it also contains major nutrients like N, S, P and K and wide variety of minor and trace elements that are bound or adsorbed onto the organic molecules or are part of the chemical structure. Soil organic matter also contributes to modulation of the broader chemistry of the soil such as pH, cation and anion exchange capacity and redox state (hydrogen ions versus electrons), thus contributing to better nutrient provisioning and expansion of possible metabolic pathways and physiological traits that can be expressed by all organisms living in the soil, including plants. There are also complex feedbacks between all elements of the agro-ecosystem.

It should also be noted that a diversity of microbial community structures or 'microbiomes' can exist in soils even within small spatial areas and biodynamic preparations, but more importantly, practices will shape those communities in different ways depending on the source materials used for the preparations and the context of the biodynamic farms themselves. It is therefore worthwhile to frame thinking about this question in terms of collective microbial community function rather than more general ecological metrics like diversity or biomass *per se*. That is, there may be no relationship between biodynamic practices, soil microbial biomass and/or a single predictable 'healthy microbiome'; instead, biodynamic practice might result in a variety of functionally analogous microbial community structures that can *all* provide adequate nutritional support and services for the agro-ecosystem. These spatial differences are likely to be reflected in the literature as variation, increased error and ambiguity in results; thus, multiyear trend observations of soil health can be more valuable than discrete point-in-time studies (Fierer et al. 2021).

As a general observation, biodynamically and organically managed soils have higher biomass, and it is assumed that this biomass represents greater diversity. However, studies of long-term field trials at the Rodale institute in the USA and Rothamsted in the UK do not necessarily support the assumption that higher biomass represents higher diversity, rather alpha-diversity is similar, but beta-diversity differs, where alpha-diversity is number of different species observed in each ecosystem and beta-diversity is a measure of the difference in diversity between ecosystems; i.e. beta-diversity includes an assessment of species that are unique to each ecosystem (Neal et al. 2020). Comparison of the same soil but managed either conventionally or via biodynamic and/or organic techniques would represent different ‘managed’ ecosystems at the alpha- and beta-diversity levels. Gamma-diversity is a measure of the total diversity (number of different types of species) across multiple ecosystems at larger geographic scales e.g. a water catchment.

To complicate matters further, understanding of soil biology is still in its infancy despite having powerful techniques to collect molecular-scale information such as genomics. Realistically, we know very little about the physiology and expression of traits for the thousands of different microbial species in soil, thus studies that link molecular-scale information to observable *in situ* function, nutrient bioavailability, plant nutrient uptake or plant nutrient density can be considered speculative with respect to assigning function to specific microbes. No references were found that combined contemporary molecular microbial ecology techniques *and* assessing plant nutrient density. Most studies looked for patterns and relationships between broad proxy measures of collective microbial community structure and function and desirable plant attributes such as nutrient density. These studies are valid and possibly more informative for biodynamic growers than dwelling on newer scientific methods that give a deep but incoherent picture that cannot accurately describe or predict function and health - except in simplified controlled systems (Frier et al. 2021).

The general theme expressed in the literature is that biodynamic preparations are rich in bacteria including plant growth-promoting bacteria and organisms that are antagonistic to plant pathogens (Olimi et al. 2022; Anil et al. 2017). Composts have also been shown to have these properties (Sriveni et al. 2004). Use of biodynamic preparations in combination with compost and manure (and other management strategies such as rotational diversity) results in general improvement in soil quality indicators such as pH and soil organic carbon, while soil microbial biomass generally increases in concert (Krause et al. 2022). Comparative studies often focus on major-element chemistry in soil, and when extending this to measuring nutrients in plant biomass, few significant differences are observed between different agronomic practices. Instead, subtle changes are more likely observed within the phytochemistry (e.g. secondary metabolites) and minor elements suggesting soil chemistry should probably be assessed from a nutrient bioavailability perspective starting with pH, cation and anion exchange capacity (CEC and AEC), along with more attention paid to calcium and trace elements. Silica also seems to be important from a plant health perspective (El-Shetehy et al. 2021). Overall, general themes emerging from the literature suggest that elevated soil health – which includes functionally healthy microbial biomass – allows plants to perform better physiologically with greater resilience to stress meaning they have better chance to adsorb the nutrients they need to thrive, with this leading to a state of ‘improved nutrient density’ overall.

5.2 Impact of biodynamic practices on soil microbial biomass structure, soil quality and soil nutrients

Biodynamic farming is considered *“above and beyond organic”* with a conceptual philosophy centred around how a farm is structured, where all aspects of the farm function together holistically as an unbroken organism. Biodynamic farming seeks to restore the soil through addition of organic matter such as manures, treating soil as a living system and finding a balance between systems that maintain life. Biodynamic practice encourages the use of green manures and cover crops, crop rotation, and treating manure and compost in a biodynamic way (these amendments are ‘living’). Biodynamics offers a path to agricultural sustainability via its effect on soil quality, the improvement of nutritional quality of produce and nature-based pest management (Muhie 2022).

It is generally estimated that 1g of soil harbours between 10^8 to 10^{10} microbial cells with thousands of different species of bacteria, fungi, archaea and viruses where composition and biomass is influenced by soil type and the inherent properties and management of those soil types (Custódio et al. 2021, Neal et al. 2020). The organisms themselves influence the soil chemistry and physics, meaning that the properties of any given soil can be quite dynamic with respect to function and health while rapid changes in microbial communities and their broader metabolic response have been observed with perturbations such as pH change after urine/urea deposition or liming, short-term anaerobicity via waterlogging, or chemical changes via fertilisation or microbial metabolism (Anderson et al. 2018). Soil biological response is therefore intimately impacted by soil chemistry and physics and *vice versa*. Any response will also be context specific so inferences can be made between sites but not absolutes.

At a high level, physico-chemical conditions that influence microbial communities include pH, moisture, nutrient availability, soil structure and temperature, with moisture and structure in turn influencing oxygenation, nutrient transport and gas exchange. Within each soil microbial community there will be organisms that have differing ranges of tolerance to all these factors and thus their functional traits are differentially expressed. Generally speaking, biodynamic soils – like organic soils – have better structure, higher carbon, more stable pH and moisture (Krause et al. 2022 and references therein), therefore it is likely that microbes expend less energy to maintain cellular homeostasis and more energy can be devoted to roles such as symbiosis and (luxury) nutrient acquisition (Käster et al. 2021). Coupled with better soil structure is higher amounts of oxygen which allow a predominance of aerobic metabolism, providing more energy for the microbes per unit of carbon consumed. Practices such as conservation tillage and organic carbon accrual change the oxidative potential within the soil (redox conditions), altering the energetics for biogeochemical processes including trace metal mobilisation (Husson 2013). Benbi & Nieder (2003) suggest that 80–90% of soil processes are mediated by microorganisms (see Custodio et al. 2022), but we are a long way from deeply understanding the ecological mechanisms and connections in soil.

Although studies have shown that crop yield can be lower in biodynamic systems, net economic returns can be equal or higher, but the true value of the benefits accrued from biodynamic soil management is likely underestimated. More importantly, soil quality is better where soil quality can be defined as “*the capacity of a soil to function for specific land uses or within ecosystem boundaries*” (Carpenter-Boggs et al. 2000a; Reeve et al. 2005; Reganold 1995). Soil quality attributes often measured include biomass and biological qualities, soil carbon storage, and available nutrients. For example, after 2 years of farming using biodynamic techniques at CISH in Lucknow, India, researchers observed increases in accessible P and K, increases in organic carbon, along with greater numbers of yeasts, moulds and bacteria (Ram & Pathank 2016). Studies in Brazil have shown that organically managed soils have lower soil bulk densities, higher soil organic carbon, higher soil respiration, greater N and available P, K, Fe and Zn compared to conventionally managed soils (Vaish et al. 2020).

In long-term trials in Sweden (K-trial, 33 years) and Switzerland (DOK trial, 28 years), it has been observed that biodynamic management resulted in greater carbon sequestration (Raupp et al. 2006). In a New Zealand trial, it was noted that microbial biomass, microbial respiration, and soil enzyme activity were all higher in the biodynamic treatment compared to organic and conventional systems on a mineral soil (Condron et al. 2000). In another New Zealand trial, 16 biodynamic and conventional farms were compared, and it was found that the biodynamic farms had higher organic matter content, greater worm populations, higher microbial biomass and activity, higher infiltration rate, better soil aeration and drainage, lower bulk density, and greater topsoil thickness (Reganold et al. 1993).

Similar to the CISH trial, Fließbach et al. (2007) found that soil pH and total N were higher in biodynamic systems compared to conventional systems within the DOK trial. Like the New Zealand trials, the DOK trial also exhibited greater soil microbial biomass and dehydrogenase activity under biodynamic management, indicating better soil quality. Opposite to the assumption in the introduction to this section: “that higher biomass will be related to higher metabolic turnover”, microbial carbon utilisation measured using the metabolic quotient for CO_2 (qCO_2) was lower in biodynamic soils compared to conventionally managed soils. Conversely, biological activity assessed as physiological efficiency in relation to microbial populations, measured as biomass C, respiration and urease activity, has been reported as being higher in soils receiving organic inputs plus fertiliser compared to fertiliser alone (Sarkar et al. 2021). Fließbach et al. (2007) suggested that the lower qCO2 might be due to higher metabolic maintenance requirement for microbial biomass in conventional soils as alluded to above. Conflicting information has been presented with regard to the soil microbial biomass C/N ratio (Cmic-to-Nmic) in the DOK trial with lower ratios reported with compost and biodynamic preparations as compared to a conventional manured system. However, this trend was not confirmed by Gadermaier et al. (2012) who stated that biodynamic preparations increased the Cmic-to-Nmic in the DOK trial.

With respect to vineyards, Döring et al. (2015) found that biodynamically and organically managed vineyards in a German a long-term trial had higher soil N concentrations. This was associated with cover crop management and compost addition. In terms of microbial activity, soil under integrated management had a significantly reduced bacterial and fungal species richness as compared to organic. This was recently confirmed used eDNA techniques (Agerbo Rasmussen et al. 2021). There was no statistical difference between organic and biodynamic treatments, and biodynamic preparations did not affect the fungal composition or richness as compared to the organic treatment (Döring et al. 2015). Fungal communities in six conventional and six biodynamic vineyards in Marlborough, New Zealand, were investigated using DNA-based molecular methods by Morrison-Whittle et al. (2017). They found that biodynamic management did not necessarily increase biodiversity, instead observable changes were habitat dependent; for example, biodiversity in soil between treatments was not different, but it was on bark surfaces.

With regard to soil organic carbon and soil carbon storage, Prairie et al. (2023) observed that increasing the number of annual crops grown per year directly increases soil organic carbon via greater carbon inputs, while at the same time increases in microbial biomass and soil aggregation raised soil carbon indirectly. Utilising perennial crops can also increase soil organic carbon. This is because perennials have larger and deeper root systems than annual crops resulting in carbon accrual as root derived carbon inputs are preferentially retained in soil compared to above-ground inputs. Prairie et al. (2023) also note that crop–livestock integration added synergy to soil organic carbon accrual, impacting multiple carbon stabilisation pathways by shifting carbon deposition below ground, modifying N use and cycling, and changing microbial parameters such enzyme activity. Utilisation of manure and urine will likely lead to similar outcomes to direct livestock inclusion except where the physical impacts of animal presence might be an advantage. Higher concentrations of soil microbial biomass and diversity were observed in farming systems where organic manures were applied regularly in comparison to systems where mineral fertilisers were used (Vaish et al. 2020).

5.3 Linkage between soil microbial biomass, nutrient acquisition and plant performance

The symbiotic partnerships that form between arbuscular mycorrhizal fungi and plants are thought to be about 400 million years old, and over the past decades it has been established that bacterial species are involved as well. Studies have shown that bacteria associate with arbuscular mycorrhizal fungi and can enhance the ability of those fungi to then form symbiotic relationships with plants, strongly promoting plant growth and enhancing N uptake (Zhang et al. 2023). Practices, such as biodynamics, that support soil fungi and bacteria will likely have a positive impact on plant nutrient acquisition, growth and health. Plants can also ‘adsorb’ soil microbes into their cells which can stimulate root hair elongation and enhance root branching which increases access to nutrients and stimulates oxidative stress tolerance (Chang et al. 2023). White et al. (2018) have long investigated the process of rhizophagy which involves adsorption of microbes from the soil where nutrients are extracted from the microbes oxidatively within the plant root. Cultivation and fertilisation practices used in conventional agriculture can therefore negatively affect the ability of plants to use microbes as a source of nutrients and impact the successful formation of symbiotic relationships.

When comparing conventional versus organic practices, Brandt & Mølgaard (2001) reported that minerals, vitamins, proteins and carbohydrates are not lacking in foods produced using conventional methods. Brandt and Mølgaard (2001) also state that pesticide concentrations are not a cause for concern, however they do not discuss the impacts of long-term chemical use nor the possibilities of negative synergistic impacts when utilising multiple chemicals together. Although Brandt and Mølgaard (2001) suggest that pesticides are not an issue (for food), there are more recent reports directly investigating the impact of common pesticides, herbicides and other agrichemicals in soil and the results vary considerably with some reports suggesting short-term benefits as microbes utilise the chemicals as carbon sources but also longer term detrimental effects for microbiomes such as lowered biomass, altered enzyme activity and induction of antibiotic resistance (Daisley et al., 2022; Kalia and Gosal, 2011; Raoult et al., 2021; Ruuskanen et al., 2023; Sim et al., 2022). To state that agrichemical use is not a concern is therefore disingenuous as Brandt and Mølgaard (2001) do not present a full picture of impacts on the whole ecosystem and downstream animal (including human) health, nor do they consider the impact on microbiome ecology and function.

Brandt & Mølgaard (2001) do however report that defence-related secondary metabolites are lower than optimal in conventional systems while organic systems often exhibit higher concentrations of antioxidants (e.g. beta-carotene, vitamin C) and secondary metabolites such as polyphenols. Whether secondary metabolite expression is stimulated via the plant microbiome relationship is currently speculated on, although there is increasing evidence that plants actively shape their microbiomes through root-secreted secondary metabolites and that strong feedback relationships exist between organisms in the rhizosphere and plants (Pang et al. 2021; Jacoby et al. 2021). Organic and biodynamically produced food has a distinct advantage in that growers can provide evidence that they are protecting the environment from anthropogenic chemicals, and their products have positive attributes like increased antioxidants. In conventional systems the direct links between the microbial life in soils and enhanced plant nutrient uptake has been demonstrated using biopriming which is the addition of singular or consortiums of bacteria and fungi (Sarkar et al. 2021). Biopriming enhances nutrient uptake and use efficiency for N, P and K. In trials in India, total N mineralisation has been shown to be 40–50% higher in treatments containing fertiliser plus manure or manure/vermicompost/neem cake/ash and bacterial amendments (*Bacillus* and *Actinomycetes*) compared to chemical fertilisers alone. Analysis of organisms in biodynamic preparations revealed four species of *Bacillus* and *Actinobacteria* with the *Bacillus* strains able to solubilise P. Inoculation with one of the *Bacillus cereus* strains from a biodynamic preparation increased maize dry weight by 21% (Radha & Rao 2014).

Improved plant performance and nutrient uptake can also be influenced indirectly via the soil microbial community. In the study by Radha & Rao (2014) mentioned in the previous paragraph, the P solubilising *Bacillus* strains also antagonised plant pathogens such as *Rhizoctonia*. Composts and soils can also exhibit varying degrees of disease suppression and act in either specific or general ways, where specific suppression involves one or a few species, and general involves a larger diversity of organisms working together (Aviles et al. 2011). Aviles et al. (2011) describes a third mechanism, specifically for compost, referred to as systemic resistance which they describe as being similar to an immune system response where compost addition increases the basal resistance level of the plant, improving plant performance. The presence of suppressive microorganisms in the finished product is important as it reflects the compost quality, and its properties as a nutrient supplier and pathogen suppressor (Hadar & Papadopoulou 2012). Avilés et al. (2011) showed that mature compost was more suppressive of fusarium infections than immature compost. Ram et al. (2019) has described the microbial consortiums of different biodynamic preparations and measured plant growth promoting attributes including ammonia, indole-3-acetic acid (auxin), siderophores (trace element mobilisation), hydrogen cyanide (plant pathogen toxicity and regulation of phosphate availability). A number of bacterial and fungal strains were shown to have the ability to inhibit fungal plant diseases (Vaish et al. 2020).

Santoni et al. (2022) reviewed the impact that biodynamic preparations and practice have on soil, primarily the use of preparation 500, and they concluded that biodynamic preparations and practice improve the overall soil quality and biodiversity. The microbial population in biodynamic preparations was found to be 10- to 100-fold higher relative to what would be expected from similar culture-dependant methods performed on soil, particularly that of preparations 502 and 506 (Ram et al. 2019). Whether small additions of preparations have any impact on overall biomass in soil is debatable; however, elevated microbial populations in biodynamic preparations that perform specific functions could explain differences in dehydrogenase, protease, and phosphatase activity in biodynamic systems compared to other management methods (e.g. that observed by Condron et al. 2000). Soluble silica (preparation 501) seems to aid plant systemic resistance to disease (Goldstein et al. 2019). Nutrient addition (mainly micronutrients), microbial inoculation, plant immunity activation, plant hormones, and microbial signalling molecules are thought to be the underlying foundations of biodynamic preparations. However, it has been noted that the small amounts of preparation material added will likely cause no measurable effect on macronutrient or even micronutrient content in soils (Muhie 2023), thus discerning the benefit of biodynamic practices and preparations requires measurement of multiple factors including microbiological changes.

As an example of the potential benefits of the microbial biomass-derived plant growth-promoting properties of biodynamic preparations, a comprehensive study comparing conventional, organic and biodynamic was published by Goldstein et al. (2019). This study reports that relative to the organic treatments, root dry matter increases associated with the use of biodynamic preparations varied from 12% to 39% and root length differences varied from 10% to 37% depending on the experiment, crop, year, and preparation application. The authors also included a biodynamic nettle- and manure-based field spray that induced substantial, positive yield compensatory effects for maize and wheat under stress condition years. The authors postulate that greater root production and root health stimulated by preparations is probably linked to greater above-ground vegetative growth, enhanced yield under stress conditions, and increased soil quality and carbon in soils.

There is a complex interplay between the plant and their root microbiome (rhizobiome). Whalen & Gul (2023) present an overview of the rhizobiome which consists of a diverse group of microorganisms that live on or around the root surface, as well as endophytes that colonise the root epidermis, cortex and vascular tissues. There is an exchange of chemical signals that are produced by and responded to by both biological partners. The rhizobiome acts as an early warning system of environmental stresses, leading to phenotypic plasticity in plant root and shoot development and the upregulation of protective functions like induced systemic resistance and antioxidant production. Plants benefit when their rhizobiome senses changes in the soil environment and the subtle changes introduced via biodynamic practices and preparations likely contribute to the positive plant physiological response observed by Goldstein et al. (2019).

Zikeli et al. (2017) investigated yield differences between 10 biodynamic and organic greenhouses in Southern Germany. In this study, the biodynamic farms had statistically significant higher tomato and cucumber yields compared to the organic farms. Although higher yields were observed for the biodynamic farms Zikeli et al. (2017) found imbalances in organic and biodynamic farms with respect to nutrient flows and were concerned about the risk of increased soil alkalinity and salinity specifically via high average surpluses for N, P, S, Ca, and Na. Biodynamic farms also exhibited a lower N use efficiency and lower concentrations of soil available P. Similar imbalances have been observed by Mayer et al. (2015) in the DOK trial in Switzerland. In Mayer at al.’s study, the conventional farming system at half standard fertilisation level had a better N use efficiency than the organic and biodynamic systems. Additionally, low organic fertiliser inputs led to degradation of soil quality in both organic and conventional systems. These results suggest that fertilisation strategies that avoid long-term nutrient imbalances in organic and biodynamic farming systems should be a focal point for research. Similar factors and concerns have also been highlighted for New Zealand soils by Condron et al. (2000). With respect to biomass and general lack of understanding of how biological communities drive soil functions, it should be noted that nutrient imbalances and inefficiencies in N use with respect to crop production might not account for the changes in microbial biomass and altered microbial community function promoted by alternative farming practices and nutrient acquisition processes such as N fixation and rhizophagy.

Beyond yield, it is also important to consider sustainability and climate change. In a study by Mäder et al. (2002), the energy to produce an organic crop dry matter unit was 20 to 56% lower than that used for conventional crops. Despite yield being 20% lower, overall organic production was considered more efficient and beneficial as nutrient input, energy, and pesticide were reduced by 34%, 53%, and 97%, respectively. Nemecek et al. (2011a,b) conclude that the environmental impacts per unit area are minimised in organic and low-input farming. The authors note that reduction of fertiliser use should not be pushed too far without risking poor crop performance, and a minimum level of nutrient supply must be maintained to ensure good eco-efficiency (Nemecek et al. 2011b). A similar conclusion was reached by Mayer et al. (2015), who found that, disregarding parameters of *long-term* soil sustainability, the conventional farming system at half standard fertilisation displayed the best performance in terms of yields, crop quality, and efficiency. The question then becomes more ecological, holistic and philosophical with respect to what the grower feels is more satisfactory for their context. Assessing farm performance with respect to soil biomass and soil carbon accrual, long-term soil health and function along with the ability of the biology to displace fossil fuel dependant agrichemical inputs make farms more resistant to inflationary forces and geopolitics. That is, microbial biomass in soil provides a massive service for agroecosystems in that the microbes use natural energy flows to aid delivery of adequate nutrition to plants as opposed to growers providing nutrients either created synthetically using, for example, natural gas, in the case of N, or mined using fossil fuels and other large-scale energy and resource-consumptive infrastructure and supply chains for creating and delivering agrichemicals.

Sustainability of agricultural production and mitigation of global warming rely on the regeneration of soil organic carbon (SOC). Prairie et al. 2023 conducted a global meta-analysis about the effects of regenerative management practices on SOC in cropland including the particulate organic matter (POC) and mineral associated (MAOC) components. They found that no-till and cropping system intensification (defined as continuous vegetation cover via increasing the number of crops grown per year, thereby increasing quantity and diversity of organic inputs returned to the soil) increased SOC (11.3% and 12.4%, respectively), MAOC (8.5% and 7.1%, respectively), and POC (19.7% and 33.3%, respectively) in topsoil. They also found no-till combined with integrated crop–livestock (ICL) systems greatly increase POC (38.1%) and cropping intensification combined with ICL systems greatly increase MAOC (33.1 to 53.6%). Microbial biomass in soil is closely linked with soil carbon processing, and microbial necromass contributes greatly to MAOC formation while fungal activity is associated with preserving POC (Cotrufo et al. 2022; Liang 2020; Liang et al. 2017; Lehmann et al. 2020). Regenerative agriculture and similar sustainable practices such as biodynamic farming are therefore key strategies to reduce soil carbon deficits derived from conventional farming practices and synthetic fertilisation. More holistic and life-promoting farming practices like biodynamics are key strategies for long-term soil health, carbon stabilisation and carbon storage, and all the other benefits associated with increased soil organic matter content (Prairie et al. 2023).

5.4 Summary

Does the microbial biomass of living soil in biodynamics, organics and conventional growing systems influence the nutrient density of food produced?

Differences in microbial biomass of living soil in biodynamics, organics and conventional growing systems are very likely to influence nutrient density, but direct evidence is lacking and much of the soil biological science is constantly evolving and discovering new things. Despite a lack of direct evidence, strong inferences can be made with respect to how the various microbial groups specifically within biodynamic and organic systems contribute to positive plant physiological response within a backdrop of (usually) increasing microbial biomass and improved soil quality metrics. Positive plant physiological response is influenced either directly, through pathways such as changes in nutrient bioavailability delivered by bacteria and fungi in the soil or indirectly through microorganisms producing plant growth promoting chemicals or controlling negative impacts such as pathogen load and infectivity. Growing systems need to be considered through holistic examination of soil-plant-microbe dynamics, along with assessing additional layers of complexity such as animal dynamics, the influence of management practices and use of various agrichemicals.

The general theme expressed in the literature is that biodynamic preparations and compost are rich in bacteria including plant growth-promoting bacteria and organisms that are antagonistic to plant pathogens. Use of biodynamic preparations in combination with compost and manure (and other management strategies such as rotational diversity) results in improvements in soil quality indicators such as pH, soil organic carbon and soil microbial biomass. Elevated soil health – which includes functionally healthy microbial biomass – allows plants to perform better physiologically with greater resilience to stress. This means they have a better chance to adsorb the nutrients they need to thrive, with this likely leading to a state of 'improved nutrient density' overall. In addition to the health benefits likely derived from more holistic and life-promoting farming practices like biodynamics, there will be climate and sustainability benefits along with ecosystem health benefits derived from avoiding the impacts of long-term agrichemical use and lower resource and energy use through less reliance on industrial inputs.

6 Consumer considerations

6.1 Consumer review approach

This aspect of the review is focused on the following questions:

- *What do consumers understand about biodynamics, compared to organics and conventional growing systems? What value do consumers place in biodynamic and organic food, compared with conventional food?*
- *Which nutrients do consumers care the most about?*

Our consumer insights study on biodynamic agriculture (Jaeger et al. 2023a) was one of the few to consider the production system in a broader rather than product specific context. Hence, we have used this as a foundation for the current review and supplemented this knowledge with the small number of product specific studies on wine that have been published. Organic agriculture by comparison has many, if not an overwhelming number of academic publications on consumer perceptions. We have observed this literature build over the last 20 years and occasionally contributed to it ourselves and, therefore, our approach has been to consider recent reviews. Regenerative agriculture is a new way to differentiate and focus on some aspects of food production, which has relevance alongside biodynamics and organic production systems – here we have relied on publications attempting to define the scope of these agricultural practices as well as occasional industry market research. However, food-related consumption behaviour has been studied for decades, and while this literature is somewhat out of scope, it is important to set a context for the review. In this respect, we consider food choice as a reflection of consumers food-related beliefs, attitudes, perceptions, and preferences and that these are strongly influenced by habitus, habits and the limitations imposed by higher prices and lifestyles that are often time-poor. Overall, we have viewed the literature in terms of how it supports, or not, the aspiration to prepare a successful SFFF proposal for research on biodynamic agriculture.

6.2 All methodologies introduce some level of bias

It is often presumed that if one asks a question (for example in a survey or interview) people will provide an answer that can be relied upon. However, responses are often biased towards what is socially positive / acceptable, for example over-representing the number of ‘good’ foods one eats, perhaps by thinking of one’s best week rather than the worst week. Fundamentally, it is important to recognise that an intention to undertake a particular food-relation behaviour (i.e. often the way questions are phrased) is poorly related to actual behaviour (i.e. what is observed in real-life). The best information comes from behavioural studies where participants do not know their food choice is being observed and/or are not aware of the true nature of what is being measured or how it is being measured and we see this in some of the contradictory information described below. Who is recruited into a study may also bias the valence of the responses. Often, participants are selected to be representative of people who usually purchase/consume the targeted product, although these participants might not represent the broader population base. Even the way data are collected can have an effect and it is important to assess data quality from online questionnaires, for example avoiding answers from internet bots/web robots and unengaged participants who click answers randomly (Jaeger & Cardello 2022).

6.3 The practicalities of food consumption

Food provisioning is greatly influenced by habits and routines, and by habitus (which is not the same as habit). Habitus is the subconscious and rarely reflected upon 'meaning of life' that allows individuals to make decisions without having to stop and think. It is the collection of experiences and knowledge that allows routines to be established and/or modified. In food provisioning decisions habitus can shape the process involved in the trade-off between preferred practices and the constraints operating at a given point of time. In many of the comments below it is arguable that it is habitus rather than 'real knowledge' that is driving consumers' selection of organic and/or biodynamic foods.

There are many factors that affect consumers' food provisioning practices. Along with habitus there are two factors that are worthwhile emphasising. Firstly, the extent that consumers do not notice product food labels as they shop. Eye-tracking studies suggest that when shopping, consumers spend relatively little attention selecting food and rather scan to find products that are already part of their food provisioning repertoire, although other studies often indicate about 27% of shoppers check nutritional information on labels when making choices (Lahteenmaki 2013). Nevertheless, the problem is that there are few opportunities to get consumers to change what they purchase and consume. The second factor relates to the time poverty of consumers that affects willingness to change from established routines. This factor has driven the high importance of convenience as a driver of food-related decision-making. Food convenience is one of the three main drivers of consumption – the others are taste and health. It is defined as: (1) no preparation or clean-up (e.g. utensils not required, not messy to eat), (2) handles well (e.g. little bruising, keeps well), (3) variety of uses (e.g. breakfast, snack, dessert), (4) suitability for entire family (e.g. liked by adults and children) and (5) high availability (e.g. long season, available in many shopping outlets) (Jaeger 2003).

6.4 Consumers' knowledge of food production systems

While some food production systems are highly recognised by consumers (e.g. 'organic food'), this does not mean people understand the detailed complexity of what is involved in producing food this way. In the same way, people generally have low understanding of sustainability of the food ecosystem – for example, in a recent study in the UK we asked 'how would you make your last meal more sustainable? The most frequent answers were about 'packaging', 'grown near your home' or 'less packaging'. Interestingly, none of the main responses regarded the sustainably of the production system (see later). These consumers did not intuitively connect the food to the way it was produced when asked the question this way. Hence many consumers when they think about food cognitively connect with its relevance to them (e.g. how safe it is to eat and what it will taste like), rather than how it was produced.

6.5 Food-related wellbeing

The importance of human wellbeing is increasingly being recognised, for example as is demonstrated by governments' budgetary focus transitioning from Gross Domestic Product to measures of wellbeing – New Zealand's first wellbeing budget was released in 2019. Wellbeing is defined as: *'the balance point between an individual's resource pool and the challenges faced'* such that *'stable wellbeing is when individuals have psychological, social and physical resources they need to meet a particular psychological, social and/or physical challenge.'* Food and its consumption at meals contributes to physical, social, psychological, and spiritual wellbeing and health, although the extent that societies recognise these diverse contributions varies – for example, studies in Brazil suggest food is perceived for its role in nutrition whereas in France there is a more nuanced and broader view of the role of meals in the social fabric of families. Consumer responses to food-related wellbeing differ according to whether they are elicited with positively or negatively framed questions, e.g. food and a sense of wellbeing versus food and a lack of wellbeing. In a PFR study of 4945 consumers (living in the United Kingdom, Australia, Singapore, or Germany) health, pleasure, food quality, positive emotions and social aspects of food consumption were the main associations with food-related wellbeing (Jaeger et al. 2022). Absence of food-related wellbeing was associated with unhealthiness, disgust, negative emotions, and poor mental health. Expanding from this, a New Zealand study of 16 different foods and beverages (912 consumers) identified that the four most important characteristics contributing to food-related wellbeing were 'Is good quality,' 'Is healthy,' 'Is fresh,' and 'Is tasty,' with the nuance that healthiness contributed most to feeling a 'Sense of wellbeing' while good quality contributed most to feeling 'Satisfied with life' (Jaeger et al. 2023b). This mixture of physical (e.g. is good quality and is tasty) and credence (e.g. it will make me healthier and live longer) attributes drive perceptions that food will contribute to wellbeing. Credence attributes are those that cannot be evaluated and verified, even after purchasing and consumption, such as country of origin or freshness.

6.6 Biodynamic food production systems

6.6.1 A study in multiple countries

To overcome the problem of asking consumers about production systems that consumers understand poorly, Jaeger and coworkers have used a text highlighting task in which participants highlighted aspects of a description that they liked and disliked. This task was undertaken with 1237 consumers drawn from Australia, UK, Singapore, and Germany (Jaeger et al. 2023a) . Using these data, sentiment analysis was conducted for individual sentences (the number of participants highlighting that they like or feel positive about a sentence minus the number of participants that highlight that they dislike or feel negative about a sentence), and this was related to other questions asked in the study. Sentiment scores are presented as percentages and can vary from -100 to +100. The text description used the phrase 'beyond organic' as well as 'biodynamic' to describe the production system, although this caused little difference to consumer responses. The terminology "beyond organic" was used as this was expected to make the text more accessible for participants who had never heard about biodynamic agriculture. The example of the 'beyond organic' text used is presented as word clouds for positive and negative highlighting (Figure 2). While there were some significant differences between countries, these were relatively small from a practical industry perspective. When segmenting consumer responses across all countries, three segments were uncovered: biodynamic positive (878 consumers), biodynamic neutral (245 consumers), and biodynamic negative (114 consumers). Note that in using this text highlighting methodology, it was important methodologically to include sentences that might be perceived negatively as well as those that will be perceived positively.

From a pragmatic perspective, the study demonstrates that most consumers view biodynamics positively with text statements regarding soil, water and biodiversity resonating most strongly. It mattered that biodynamic agriculture was a balanced and integrated approach to farming/food production. Biodiversity and other aspects of environmental sustainability were more important than social sustainability, notably worker welfare and community resilience. The negative sentiments were associated with sentences 18, 19 and 20 – respectively: *'But it can also be seen as non-scientific with links to magical thinking'*, *'Farmers making decisions about when to plant and harvest based on the positions of the sun, moon and stars is one example'* and *'Another example is the use of mixtures of* *cow dung and herbs because they are seen to boost soil and plant fertility'. However, in a subsequent study (Ares et al. 2023) it was found that the negative highlighting was not because consumers disliked these aspects of biodynamics, but rather they disliked the negativity of the statement and/or the right of others to make such criticisms about others'* production systems.

Liking

Disliking

Figure 2. Word cloud showing text-highlighting responses (liking and disliking) UK consumers to descriptions of biodynamic agriculture practices. The larger the font and darker the colour, the more frequently words and phrases were highlighted (from Jaeger et al. 2023a).

6.7 Studies on consumer response to biodynamic wine

Interviewees from several countries (excluding France and the USA) did not clearly see the differences between sustainable and organic or biodynamic wines, which is most likely because of their lack of knowledge (Szolnoki 2013). In a 2010 a comparison of 400 USA consumers' responses to organic and biodynamic wine (69% had heard of organic wine and 41% had tasted it; 18% had heard of biodynamic wine and 8% had tasted it; 19% indicated they understood the difference) found that 'consumers with knowledge of organic wine tended to have a more positive attitude towards biodynamic wine' and 'the definition of biodynamic wine with terms related to the quality of the grapes was better received than the more traditional definition describing the crop growing approach' (Delmas 2010). Troinano et al. (2020) provided 101 Italian consumers with conventional and biodynamic wine, and tested consumer responses in blind condition (tasting without information), expectations (information only) and in 'real situation' (tasting and information). Levels of recognition of organic and biodynamic wine were similar to those recorded by Delmas (2010) and liking of wine was similar in the blind condition – the study demonstrated that provision of information increased consumer liking for biodynamic but not conventional wine.

While these studies are useful in understanding consumer knowledge and responses to biodynamic agriculture, it should be noted that wine cannot carry health messaging (i.e. nutrient claims) because of its alcoholic content.

6.8 Organic food production systems

From a consumer research perspective, 'organic foods / beverages' represent words that western consumers universally understand as products that should be at the very least be 'better for you', with more knowledgeable and engaged consumers having a more complex understanding of the benefits to them personally and to the planet. As such, it is not unusual for consumer scientists to use the word organic as a simple shortcut that prompts as sense of wellbeing in food-related consumer studies as well as studying consumer attitudes, perceptions, and preference for organic food production for its own sake. As simple search of the Web of Science using the keywords Consumer* AND Food* AND Organic* uncovered more than 7000 articles – a good indication of the scale of academic interest on this topic. Commercially, searches of databases such as the Mintel new product database indicate that 'organic' represents an ever-growing food trend in the global marketplace.

We have been focusing on recent reviews: 'The consumer perception and purchasing attitude towards organic food: a critical review' (Roy et al. 2023), Consumer behaviour and purchase intention for organic food: a review and research agenda (Rana & Paul 2017), 'Can't buy me green? A review of consumer perceptions of a behaviour towards the price of organic food' (Aschemann-Witzel & Zielke 2017), 'How important is country-of-origin for organic food consumers? A review of the literature and suggestions for future research' (Thorgerson et al. 2016), 'The willingness to consume organic food: a review' (Eyinade et al. 2021) 'Consumer perceptions towards organic food' (Shafie & Rennie 2012), and a recent study on Australian organic consumers (Sultan et al. 2018). As such some of the content reflects comments and conclusions in publications other than those cited (i.e. this section is a review of reviews).

Consumers are increasingly conscious of health and lifestyle choices, and can distinguish between healthy and conventional foods items, and this knowledge is resulting in increasing sales of organic foods in western and developing nations (Roy et al. 2022), which is often prompted by extensive media coverage on health-related topics (Rana & Paul 2017). It is usually assumed that consumers of organic foods are highly involved and knowledgeable about food in general, and willing to spend effort to understand information regarding differentiated food and beverages (Thogersen et al. 2017). 'Organic' is a credence attribute and therefore consumer trust is a prerequisite for establishment and growth of the market – thus, mistrust fuelled by media scandals, inconsistent standards and assessment practices can be problematic (Thogersen et al. 2017). In the review by Roy et al. (2022), the factors influencing positive perception of organic food were: (a) health, (b) quality standards and food safety, (c) eco-friendliness and moral purchasing, (d) cost-effectiveness (i.e. perceived benefit relative to price), (e) a negative response to higher prices linked to risk that products might not be authentic (e.g. organic certification), and (f) fashion trends and lifestyles. Rana and Paul (2017) focused more on purchase intentions and identified the following factors:

- Health consciousness and expectations of wellbeing are considered the best predictors of attitude and behaviour towards organic food.
- Perceptions of higher quality and safety of organic foods based on consumers' concerns relating to use of pesticides and other agricultural chemicals in conventional production, which also taps into the perception that industrialised food production also creates risks from food-related pathogens (e.g. mad cow disease).
- Environmental friendliness and ethical consumerism. There is some overlap with the preceding factor in that perceptions that agricultural chemicals are not used in organic production is important, although in this case the desired outcome is the more altruistic ecological / environmental benefit rather than personal. Consumers responding this way are responding to fulfil their perceived ethical responsibilities.
- Willingness to pay – consumers are willing to pay a premium according to surveys in many countries.
- Price and certification – high prices and a lack of awareness of benefits of organic produce are often disincentives for purchase and consumption. However, farmers can increase their consumer base by improving the distribution channels and through certification that authenticates and validates their products.
- Fashion trends and unique lifestyles – In the USA and Italy (and we are aware of similar observation in South Korea) consumption of organic foods may be a status symbol.
- Social consciousness – In one cited 2006 study in the UK, 65% of consumers of organic foods from 'Eostre Organics' desired 'to support and strengthen the local economy and community, including greater self-reliance and independence from global corporations and supermarkets.'
- There are different consumer needs associated with different countries – in western countries the attitude and behaviour to organic foods reflect consumers ethical commitment, safety, knowledge, and health, whereas in developing countries the factors are availability, education, health, marital status, and family size are very important.

Generally, the reviewed literature confirmed the above list, and expanded into tangible product attributes of nutritive value, flavour and texture, freshness, and appearance (Shafie & Rennie 2012). In other words, there is an expectation that credence value (that it will be better for you), should have a tangible outcome that you can see and taste – in an accompanied visit to a supermarket in China, a consumer pointed to organic lettuce and said: *'that is expensive, I purchased some a while ago, but it* *didn't taste any different so I didn't buy it again'* (pers. comm. RH). Shafie & Rennie (2012) noted in their review that comparisons of sensory properties of organic and conventionally grown foods were inconsistent (Shafie & Rennie 2012). We consider taste in more detail later.

Data on New Zealand consumers' attitudes towards organic foods can be found in a report by Organics Aotearoa New Zealand (2021). The consumer attitudes were collected as part of an omnibus survey (i.e. did not specifically recruit organic consumers). While the datasets are not presented in a format that allows academic review (and there is no statistical analysis), they have face value and reflect the broad understanding of behaviour presented in the current report. Some of the findings differ from those presented in a more directed Australian study (e.g. influence of income on consumption; see Section 6.10) and this could reflect slight differences in culture on either side of the Tasman Sea, as well as different methodologies and recruitment approaches.

6.9 Value and willingness to pay for organic and biodynamic food

The most useful review is that written by Aschemann-Witzel & Zielke (2017) on perceptions and behaviour towards price of organic produce. They position the article alongside the FAO's and UN's acknowledgement of the potential of organic farming to contribute to sustainability goals, the ambitious goals of European countries to increase the share that organic farming plays in food production, and the need to understand what is hindering further growth of markets for sustainable foods in general and organic foods in particular. Five questions are posed and addressed:

- How important is price as a perceived barrier to organic food choices?
- What is the role of income in the purchase of organic food?
- How exact is consumers' price knowledge of organic food?
- How high is consumers' willingness-to-pay' for organic food?
- How do consumers react to pricing measures for organic food in the marketplace?

Most studies (12 out of 16) find that consumers report that price is the primary barrier to consumption. The remaining four studies related to countries where the market was in the early stages of development or very mature markets. In the undeveloped markets, lack of information and availability were more important than price and in mature markets quality and diversity of products were more important than price. Price was also suggested as an important in the self-justification of organic purchases. For example, occasional purchasers of organic food use price to justify continued purchase of conventionally grown food, while regular consumers focus on the value and rationalise according to health outcomes and ethical issues.

There were mixed findings on the influence of income, although in general, it influenced purchases of organic food. The reviewers commented that the income-consumption relationships were complicated by sociodemographic and psychographic factors as well as education, presence of children in families.

Aschemann-Witzel & Zielke (2017) concluded that knowledge of organic food prices is low and inexact, although noting that research addressing this topic was rare. In one cited study, organic consumers were interviewed before entering a store about their price expectations and maximum willingness to pay and then were unobtrusively observed regarding their choices. The conclusion was *‘consumer price knowledge is rather fuzzy and observed consumers purchasing above their stated willingness to pay. Knowledge was more exact for consumers who purchased frequently, compared prices, and stated price as important and lower for higher-income consumers and those working full time.’* In another cited study the researchers commented that: *‘consumers general price knowledge is outdated and organics have a persistent “high-price image,” which might explain the association with “elitist” and expensive.’* The sentiment that consumers often expected prices to be higher was reflected in the findings in several studies.

Consumers are generally willing to pay more for organic food. The percentage increase over conventionally grown foods varies according to the product and country: 1% to 10% meat in Ireland, 50% for wine in Germany, 1% to 5% for milk in Denmark, 35% to 105% for chicken in the USA. The great variation in reported willingness to pay is probably due to a number of factors including: the food category with some “virtue” categories having higher willingness to pay for organic products, the percentage of organic ingredients in manufactured foods, local origin, and the observable quality of the product, past experiences with organic foods, and the level of knowledge. On average, the review suggests and average of 30% premium for organic foods. In general, the literature concluded that organic consumers were less reactive than conventional consumers, but nevertheless responsive to pricing and that regular consumers differ from occasional consumers.

Fanasch & Frick (2020) undertook economic modelling of 55,500 wines produced by 1514 German wineries listed in the wine guide ‘Gault Millau’ between 2010 and 2017 to understand the impact on price of organic and biodynamic wines sold with certification or as self-declared organic or biodynamic (i.e. without certification). The models suggested that self-declared organic wines increased the bottle price by 8.61% and with certification the price premium was 5.77%. For biodynamic wines, self-declared wines were sold at a discount of 8.07% per bottle while certified biodynamic wines charged a premium of 4.05%. The authors (Fanasch & Frick 2020) used these results to confirm their hypotheses:

- Organic self-declaration increases the price charged for a wine.
- Organic certification increases the price charged for a wine.
- But, because biodynamic practices are less credible, not fully understood or appreciated by consumers, biodynamic self-declaration decreases the price charged for a wine.
- Biodynamic certification increases the price charged for a wine.

6.10 Segmenting the Australian organic food consumer market

A recent online study attempted to segment the Australian organic consumer market (Sultan et al. 2018). A random sample of 1011 consumers from a national research panel covering all states and territories completed the survey. To qualify for inclusion the respondents were over 18 years and had purchased and consumed organic food products at least 6 months prior to the survey. The self-reported behavioural measures were: (1) average weekly household expenditure for organic foods, (2) length of period consuming organic foods as an indicator of loyalty to the product, (3) purchase frequency of organic foods.

The study found:

- Demographic variables such as gender and marital status do not significantly influence expenditure or loyalty status.
- Annual household income influenced expenditure and loyalty. Organic food consumers were skewed to low- and high-income households; 49% of consumers with an income from $45,000 to $105,000 have consumed organic food for more than 3 years.
- Education had a significant influence on expenditure, but not loyalty.
- Age significantly influenced both expenditure and loyalty.
- Consumers living in metro/city areas had higher usage rates and loyalty than those in rural/regional areas. There was no significant difference between states.
- Psychographic variables 'perceived values'[4], 'self-image'[5] and perceptions about organic foods[6] were all significant in segmenting organic consumers.
- Based on the psychographic responses, two specific consumer segments were identified – based on "Excitement" and Wellbeing". The excitement segment is excited and enjoys shopping for organic food, while the wellbeing segment is responding to environmental, ethical, and chemical free priorities.
- Weekly expenditure and loyalty to organic foods are independent and not associated.
- Most consumers spend less than $100 per week on organic food and this is consistent for consumers who have been consuming organic food for less than a year as well as those consuming for more than 3 years.
- The retail outlets that consumers go to purchase organic foods are Coles (32% repeat purchases), Woolworths (30% repeat purchases), farmers markets (13% repeat sales), direct from producer (6% repeat sales), health stores (11% repeat sales).

6.11 Taste perceptions

Consumers often express an expectation that organic foods taste better than conventionally grown foods, although such sensory differences are inconsistent in formal studies (see earlier comments based on the review by Shafie & Rennie 2012). PFR has been involved in such comparisons in the past (Harker et al. 2009) and has provided critical assessments on the difficulties in undertaking such comparisons (Harker 2004). Consumer-sensory science of natural foods is deconstructive by its nature in that if you do not control for all the product variables one will just get the unexplainable noise/variability that reflect variability in consumer preferences (human genetics demonstrate that

[4] Perceived values assessed according to questions about: health-promoting effects, live a healthy lifestyle, enhances ones health, one's health consciousness, keeping a healthy work-life balance.
[5] Self-image assessed according to questions about: purchasing organic food makes one feel good, enjoyment in spending money on organic food products, eating organic food is one's desire, enjoy new experiences of trying organic food, treating oneself by eating organic foods, best time to enjoy organic foods is during meals.
[6] Perceptions about organic foods assessed according to questions about: superior quality, no harmful effects to health, superior taste, good for the environment, shopping for organic foods is truly joyful, pleasure to shop for organic foods, shopping for organic food is an exciting experience, free from chemical residues, not contaminated by chemicals, maintains high food safety standards.

everyone lives in their own flavour-world and even when the genetics are similar, individuals express different likes and dislikes for the same food). For example, in comparisons of organic and conventionally grown kiwifruit, one needs to ensure that fruit are ripened to the same point. When this is done and dry matter concentration is matched, there is no perceived difference in consumer liking – suggesting that industry taste standards can apply equally to organic and conventionally grown kiwifruit (Harker et al. 2009). Furthermore, some aspects of production and supply chain management not fundamental to core organic/conventional philosophies may influence quality and taste of products. Thus, sampling of foods intercepted in the marketplace may confound the comparison of the production system with extraneous factors in the supply chain (Harker 2004). By far the biggest issue, is the fundamental question of how to compare two or more production systems. For example, if we are setting a universal quality standard for a fruit industry, we would recommend that we need samples from at least 10 orchards. Thus, to compare fruit from a single organic orchard and single conventionally orchard is not sufficient to demonstrate a production system effect.

6.12 Regenerative food production systems

There has been a major pan-country and pan-sector review regarding the definition and role of regenerative practices in the context of New Zealand agricultural systems. In the end the group of collaborators (71 authors) indicated: '*We don't offer a definition of RA for two reasons: the benefits of defining RA are disputed (as we subsequently discuss), and in NZ any such definition would need to be anchored in te ao Māori, the Māori worldview, and the goals, visions, priorities and aspirations of whānau, hapū, iwi and Māori corporations for how kai (food) is produced, and how whenua (land), wai (water), and rangi (sky) interact with tangata (people).'*

The review goes on to usefully point out from the perspective of this consumer review that the impetus for Regenerative Agriculture is: *'a global, grassroots, farmer-driven movement founded on an ecological paradigm addressing failings in our current global food system. The Regenerative Agriculture movement acknowledges that farmers can become part of the solution to mitigate or reverse the negative environmental impacts of our current food production systems. However, Regenerative Agriculture is much more than a system of farming: it is a mindset that questions the status quo, and instead of becoming defeatist sees opportunities for different ways of living, working and farming. Regenerative aligns with growing worldwide societal and consumer demands for safer, healthier, environmentally sound food systems, and engages in innovative processing and marketing.'*

The viewpoints in the last sentence align with those that resonate with consumers as identified in Section 6.6 on Biodynamic Food production and, indeed, with Rudolf Steiner's principles that led to the development of the Biodynamic movement. As such, from a consumer perspective Biodynamic Agriculture is arguably an older and well-established subset of Regenerative Agriculture. However, the term Regenerative Agriculture does cause problems for consumers (below), whereas speculatively Biodynamic may not.

There are three studies on consumer perceptions of Regenerative Agriculture that have been considered: Beef and Lamb New Zealand (2021), Tait et al. (2021) and Research First (2023).

Beef and Lamb New Zealand (2021) produced a report - Regenerative Agriculture: Understanding the current state and future potential of Regenerative Agriculture in the United Sates, United Kingdom, and Germany – Consumer Insights). This was an online survey with responses collected as quantitative as well as open ended questions from a relatively small sample of consumers (USA = 47, UK = 41, Germany = 45) of which most significantly 69% or more were Conscious Foodies (i.e. suggesting a high engagement with food that is beyond the average population). It provides a strongly positive view of the opportunities for regenerative agriculture in overseas markets summarising them as:

- Consumers are primed for engagement in the Regenerative Agriculture Revolution
- Regenerative Agriculture can be the win-win-win for taste-health-planet that consumers are looking for
- Preference for local may present a challenge for New Zealand
- People will pay more for Regenerative Agriculture and Sustainably Produced food—and even more once they learn more about it
- The pull of purpose and personal benefits for paying a premium
- The top three communication approaches across all countries matched top drivers of food choices overall—and the need for simplicity:
    - 'Restoring ecosystems and soil health'
    - 'Addressing the climate crisis'
    - 'Providing more nutritious, delicious food'

Tait and coworkers (2021; Regenerative Agriculture: Knowledge, perceptions, and product preferences in the United Kingdom and California) ran a survey on consumer perceptions of Regenerative Agriculture with 1000 consumers in each market. It should be noted that California is probably a more liberal and supportive than markets in ‘Middle America’. Results were similar for and aligned in both markets. The key relevant findings were:

- Knowledge of regenerative agriculture:
    - No knowledge: 60% UK, 62% California
    - A little bit: 27% UK, 23% California
    - A moderate amount: 10% UK, 10% California
    - A lot about: 4% UK, 3% California

  It should be noted that this might differ if asked as an open-ended question such as ‘describe what you understand about Regenerative Agriculture.’

- Factors that are associated with regenerative agriculture, ranked (for convenience) according to the percentages of consumers responding as having a ‘strong association’ in the UK (note ranking differs slightly in California):
    - Care of the environment, 51% UK (44% Cal. = minus 7%)
    - Restoring ecosystems and habitats, 47% UK (38% Cal. = minus 9%)
    - Soil health, 45% UK (40% Cal. = minus 5%)

    - Animal welfare, 43% UK (30% Cal. = minus 13%)
    - Socially responsible production: 42% UK (33% Cal. = minus 11%)
    - Ecological health, 41% UK (40% Cal. = minus 1%)
    - Reduced carbon emissions, 41% UK (36% Cal. = minus 5%)
    - Natural methods, 41% UK (34% Cal. = minus 7%)
    - No synthetic chemicals, 40% UK (34% Cal. = minus 6%)
    - Waste reduction, 39% UK (36% Cal. = minus 3%)
    - Organic production, 38% UK (35% Cal. = minus 3%)
    - Higher biodiversity, 38% UK (29% Cal. = minus 9%)
    - Mimics natural processes, 36% UK (30% Cal. = minus 6%)
    - Care of traditional cultures, 30% UK (22% Cal. = minus 8%)
    - Holistic management, 27% UK (26% Cal. = minus 1%)
    - Round-up free, 26% UK (32% Cal. = plus 6%)
    - Carbon capture, 26% UK (26% Cal. = minus 0%)
    - High productivity, 22% UK (29% Cal. = plus 7%)

  Note that percentages of consumers in California were generally lower than in the UK, and this was most obvious for 'restoring ecosystems and habitats', 'socially responsible production', 'higher biodiversity', and 'care of traditional cultures.' By comparison, the percentages were higher in California than the UK for 'Round-up free' and 'High productivity.'

- The importance of regenerative agricultural product attributes, ranked (for convenience) according to the percentages of consumers responding as having a response 'very important' in the UK (note ranking differs slightly in California):
    - Reduced environmental impact of production, 49% UK (36% Cal. = minus 13%)
    - Animal welfare, 48% UK (38% Cal. = minus 10%)
    - Sustainable products, 47% UK (39% Cal. = minus 8%)
    - Eco-friendly production, 46% UK (42% Cal. = minus 4%)
    - Natural products, 45% UK (35% Cal. = minus 10%)
    - Socially responsible production, 45% UK (35% Cal. = minus 10%)
    - Higher quality, 44% UK (35% Cal. = minus 9%)
    - Healthy food, 43% UK (39% Cal. = minus 4%)

- No additives, 41% UK (35% Cal. = minus 6%)
- GM-free, 38% UK (30% Cal. = minus 8%)
- Better taste, 34% UK (35% Cal. = plus 1%)
- Care for traditional cultures, 33% UK (36% Cal. = minus 7%)
- Organic, 32% (33% Cal. = plus 1%)
- Local food, 30% UK (27% Cal. = minus 3%).

Again, the responses from Californians are generally lower or the same as those from UK consumers. Notably, responses to 'reduced environmental impact of production', 'animal welfare', 'sustainable products', 'socially responsible production' and 'higher quality' suggest that these are less important to Californians than residents in the UK.

Research First is one of few research companies in New Zealand that has an inhouse operations facility. In a 2023 project, (Buying green) it canvassed consumer perceptions of regenerative agriculture, although the numbers of participants are not presented. The study included a series of questions of regenerative agriculture which started by asking 'Have you heard the term regenerative agriculture?' 47% of consumers had not, 36% indicated that they had heard the phrase, but did not know what it meant, and 18% indicated that they heard the name and knew what it meant. The questionnaire went on to describe regenerative agriculture focusing on benefits of reversing climate change by rebuilding soil organic matter and restoring soil biodiversity. They went on to ask if there were two similar products, one produced product through regenerative agriculture and the other through standard farming practices, would they pay more for the regenerative agriculture product? 38% said no, 32% would pay less than 5% more, 18% would pay up to 18% more, 3% would pay up to 15% more, and 10% would pay more regardless of the price. Such results are reassuring for those involved with or contemplating investing in regenerative agriculture but are hypothetical because willingness to pay assessments usually need to be asked about specific products – for example the price and percentage increase in price may be different when purchasing a bottle of wine or a bag of potatoes.

Two of the above studies were conducted in the UK. As a caution to the optimistic views of the opportunities they suggest, we point to a recent online study we conducted on sustainability with UK consumers (Hutchings et al. 2023). In one of the final questions asked to 1522 UK consumers we asked: Please think of the eating occasion you described earlier. How could this eating occasion have been more sustainable (response were as text written by participants)? The 10 most common responses were: nothing it was already sustainable (18%), do not know/unsure (15.7 %), brought food produced locally (14.4%), brought food that used a different type of packaging (12.5%), used less electricity to prepare the meal (7%), made it at home (6%), removed meat/seafood/dairy (5.5%), used a meat/seafood/dairy alternative (4.7%), reduced my food waste (3.6%) and recycled the packaging (3.4%). Re-screening the data for participants who used the words 'regenerative', 'biodynamic' and 'organic,' we found only 48 (i.e. 3.1 %) of participants used 'organic' – none used the other descriptors. This arguably suggests that changing to a more sustainable production system was not at the front of British consumers' minds when they thought about making their meals more sustainable.

6.13 Synopsis and opportunities: biodynamics

What do consumers understand about biodynamics, compared to organics and conventional growing systems? What value do consumers place in biodynamic and organic food, compared with conventional food?

Societies' views of food are undergoing a renaissance as they look towards 'values-based agricultural production systems' that are more sustainable for the planet and healthier for people. To some extent, this represents an accelerating change away from industrialised food production that originally prompted the creation of organic and biodynamic movements in the 1940s. The new concept that agricultural production should be regenerative is widely supported although the technical details of how to measure progress towards this biological and environmental outcome remain uncertain and, in New Zealand, it is recognised that Te Ao Māori values should shape any definition. In discussing 'values-based agricultural production systems,' it would be short-sighted to separate consumers from gate keepers and stakeholders in the food production and supply chain. The knowledge, views and values pass in both directions. Consumers must trust the decisions made on their behalf by retailers or they will shop elsewhere.

We have reviewed consumers knowledge of three 'values-based agricultural production systems': regenerative agriculture, organic agriculture, and biodynamic agriculture. In many respects, the data are best viewed as universal understanding of these systems rather than as differentiating them from each other (except for a segment of highly engaged individuals) – although, organic foods are a useful case study because 'organic' is more recognised. Across all these production systems, consumers are responding positively to messages of care for the soil, groundwater, and wildlife to build healthy ecosystems and rich biodiversity. Arguably, it is the values and philosophies that drive the way organic and biodynamic growers manage their land that offer the greatest opportunity to connect with consumers although there are some counter arguments to this. Most growers and farmers using more conventional production systems argue for the same outcomes but are handicapped by consumers mistrust of industrialised food production that use synthetic fertilisers and crop protection methods. Thus, for organic and biodynamic foods, consumers are responding to their perceptions that these are safer and healthier because they are more natural and 'not sprayed'. However, these perceptions may not be sustained in public health and/or large meta-analysis, but rather reflect habitus (subconscious and rarely reflected upon 'meaning of life' that allow individuals to make decisions without having to stop and think) that have accumulated over time for a particular group of highly supportive organic and biodynamic consumers.

The low level of knowledge consumers hold for any production system probably means that it is unrealistic to expect them to meaningfully differentiate between any values-based system such as organic, biodynamic, and regenerative. However, it is worthwhile considering how well they are recognised. When UK consumers were asked how they would improve the sustainability of their last meal, 3.1% of consumers mentioned organic in their descriptions of how to improve sustainability and none mentioned biodynamic. Interestingly, when consumers were asked to write down four words associated with food and a sense of wellbeing, 3.9% consumers mentioned the word organic (sample size was 150 consumers from each of UK, Australia, Singapore, and Germany; Jaeger et al. 2023a). Of course, if researchers prompt consumers that the focus of a survey is on organic, biodynamic, or regenerative foods, the level of recognition and support for these becomes much higher – for example Tait et al., suggest 38% to 40% of USA and UK consumer have at least some knowledge of regenerative agriculture – the newest of these production systems. Thus, we conclude that when asked open-ended questions about food (i.e. without any prompting about organic production) about

3% to 4% of consumers discuss organic food as being more sustainable and better for human wellbeing – it is the most recognised and front-of-mind food production system.

6.14 Which nutrients do consumers care the most about?

The literature regarding how consumers respond to nutrients is overwhelmingly large. A starting point for PFR occurred some years ago when we wanted to understand why some consumers chose to eat fruit while other chose to take supplements to meet their nutrient needs. We undertook focus groups of 55 participants who (1) ate fruit, (2) relied on supplements or (3) were occasional users of supplements (Lau & Rossiter 2001). A memorable outcome was that those that who trusted conventional agricultural production chose fruit and those who did not trust agricultural production chose to use supplements sometimes as a back-up in case fruit failed to deliver their daily requirements. There are many conversations about the depletion of nutrients in soils – for example one supplement user said: '*Even our soil doesn't have the nutrients it did 30 years ago. If it's not in the ground, we can't possibly get it in our veggies.'* Thus, there is a strong linkage between trust in agriculture and foods to provide good nutrition and the perceived need take supplements for one's health – which obviously informs Kite Ora Trust's mandate to promote organic and biodynamic production of food.

Consumers are more responsive to messages regarding the outcomes of food-related nutrition such as improved physical and mental performance, improvements in wellness and wellbeing, and avoidance of specified diseases. As Lahteenmaki (2013) notes: *'one factor closely linked to consumers' responses to health claims is familiarity, whether it be familiarity with the functional compound, health benefit, health claims per se or product categories as carriers of health claims.'* Spiro and Wood (2021) argue that the nutrition messaging is a crowded space and new messages increase confusion rather than provide clarity and demonstrate this point with a quote from one of the professionals they interviewed: *'more information on nutrients may give people more insight into the healthiness of foods but is more information more confusing? – it's how it's explained.'* Nevertheless, consumers face a barrage of information from the media and by professionals with advice on nutrients and nutrition. Consumers tend to categorise nutrients into those that are good and those that are bad. The latter include salts, sugar and fat which we are disregarding in this review as the focus is on more positive nutrients.

There are some nutrients such as iron, calcium, vitamin C, vitamin E, folate, dietary fibre that are well recognised as being important by the public and are sought by people who have or perceive themselves to have specific deficiencies that are affecting their health (e.g. those in Table 4). Other minerals are known to be deficient in populations because of deficiencies in local soils (e.g. selenium in New Zealand).

Table 4. Nutrients added to foods and their benefits (after Bakshi et al. 2020).

Nutrient	Benefit
Folic acid	Helps in foetal growth
Iodine	Promotes thyroid health and reduces heart disease
Vitamin A	Important for night vision and improves skin health
Vitamin B	Vitamin B12 and vitamin B6 reduce the risk of heart disease
Vitamin C	Improves absorption of iron and boosts immune functions
Vitamin D	Helps in the absorption of calcium
Vitamin E	Prevents heart disease and reduces of Parkinson’s disease
Iron	Reduces anaemia
Copper	Protects cells from damage
Magnesium	Manages cardiovascular health and strengthens bones
Phosphorus	Essential for bone health
Zinc	Maintains thyroid function, improves heart health and boosts immunity
Calcium	Improves bone strength
Selenium	Prevents cardiac muscle degeneration and reduces the risk of cancer
Omega-3 fatty acids	Reduces risk of heart diseases, reduces blood cholesterol, improves mental functions
Probiotics	Helps in digestion, boosts immunity, and lowers respiratory tract infections

Recent qualitative studies in Australia on perceptions of nutrient content claims found four interconnected themes (Thompson et al. 2023):

- There are many interrelated factors that influence food and drink purchasing.
- Content claims are regarded with scepticism.
- The functional difference between content claims and health claims is unclear.
- Most consumers are unaware of the regulation of content claims.

Given the focus of this review, we have concentrated on consumers’ perceptions and understanding of the concept of nutrient density (discussed in section 2.3). The concept of nutrient density was suggested as an approach to take a more holistic vision of nutrient quality into consideration (Miller et al. 2009) and nutrient dense foods are specified in US Dietary Guidelines (USDA/HSS 2020) as the foundation of healthy eating. In a related concept, the nutrient rich density index balances several nutrients to encourage (e.g. protein, dietary fibre, vitamin A, vitamin C, Vitamin E, calcium, iron, K, and magnesium) against three nutrients to limit (saturated fat, added sugar and sodium, using a 100 kcal as the basis of the calculation. Spiro & Wood (2021) noted that there was no universally agreed definition and a paucity of information about what UK consumers understand about the concept – the topic had been canvassed in a round-table event by the British Nutrition Foundation. They went on to provide information on consumer and experts understanding of nutrient density in a publication titled: Can the concept of nutrient density be useful in helping consumers make informed and healthier food choices? A mixed-method approach (Spiro & Wood 2021). They interviewed consumers representing pre-family with an interest in wellbeing, parents of school-aged children, weight managers, and healthy agers, as well as medical professionals including dieticians, before going on to run online surveys of 2133 consumers and 98 registered nutrition professionals – a substantial study. Focusing on results specifically relevant to the current consumer review we reproduce results from three tables (Table 5).

Table 5. Consumers and Registered Nutritional Professional in the UK's understanding of the term 'nutrient density' after Spiro and Wood (2021). Note that the US Dietary Guidelines define nutrient dense as foods that provide vitamins, minerals and other health-promoting components and have little added sugars, saturated fat and sodium.

Consumers (N = 2133)	**Response rate**
Question: Thinking specifically about food… Which one of the following statements best describes how familiar you are with the term 'nutrient density'?	
I know what it means and could explain what it means to someone else	11%
I think I know what it means but I am unsure that I could explain it to someone else	25%
I have heard of it, but do not know what nutrient density means	15%
I have never heard of it	50%
Consumers (N = 2133)	
Question: Which one, if any, of the following best describes what you think 'nutrient density' refers to?	
The amount of beneficial nutrients in a food (i.e. nutrients we should be including in our diet)	49%
The balance of 'good' and 'bad' nutrients there are relative to the energy (calories) content in a food	21%
The food being a source of vitamins and minerals and relatively few calories	7%
A food being high in calories but also nutrients	3%
The amount of 'bad' nutrients in a food (i.e. nutrients we should be limiting in our diets)	2%
The food being low in calories	1%
None of these	2%
Don't know	16%
Registered Nutritional Professional (N = 98)	
Question: What best describes your definition of a nutrient-dense food?	
A food that has a low amount of nutrients we should be limiting and a high amount of nutrients to encourage, relative to its energy content	34%
A food that has high amounts of any nutrient, whether nutrients to limit or nutrients to encourage	24%
A food with a high ratio of vitamins and minerals and fibre compared with nutrition requirements	20%
A food that provides substantial amounts of vitamins and minerals and relatively few calories	10%
A food that is recommended in the Eatwell Guide	2%
Other	9%

The results suggest there is little detailed understanding of the term 'nutrient dense,' although it is perceived as being a positive attribute. Spiro & Wood (2021) go on to discuss the needs for food labelling in communicating nutrient density to consumers.

6.15 Synopsis and opportunities: nutrient density

Which nutrients do consumers care the most about?

Consumers are often confused by messaging about nutrition, and with manufactured foods messages that a food is heathy is often confounded by an expectation that it will not taste good (i.e. it is low in fat, sugar, and salt). There are few studies on consumers' understanding and perceptions of the term nutrient density and the issue has not been canvassed across many countries. In the study we have reviewed, consumers perceived the term positively immaterial of whether their understanding was correct or not. But only 11% were confident about understanding the term, and thus there may be a risk in using 'nutrient density' in communicating about the advantages of biodynamic agriculture. Rather, the consumer opportunity for biodynamics in engaging with nutrition in this way may be akin to the position of the blueberry sector in the early 2000s when research on health benefits was relatively passively promoted by industry but actively picked up by the media as summarised by Crawford & Mellentin (2008): *'The development in the West came as a result of journalists picking up on the news emerging from the science and this attention has maintained a momentum all of its own from a media eager for positive stories about appealing, naturally nutritious foods.'*

7 Overall conclusions and future work

The key findings of this report are:

- Nutrient dense foods are important for health because they deliver more of what the body needs for good health (i.e. vitamins, minerals, complex carbohydrates, protein and healthy fats) and less of what it does not need as much of (i.e. saturated fat, sodium and refined sugars). Nutrient dense foods are needed to build all the body tissues but are also essential for many healthy bodily functions such as a healthy immune system, lowering the risk of non-communicable diseases (e.g. diabetes, cardiovascular disease, osteoporosis), assisting with weight management, improving digestion and can also lead to better mental health.

- Each food has its own distinct nutritional and phytochemical profile. Nutrient density measures have been used in an attempt to assess the overall nutritional value, and hence potential health benefits, of foods. There are various different measures/tools that have been reported in the literature. However, no existing published nutrient density tool is probably appropriate for the study of impacts of growing practices on composition. This is because the tools are limited in which nutrients and phytochemicals are included and may not have sufficient granularity to distinguish changes in particular subsets of nutrients specific to an individual crop.

- Some evidence suggests that biodynamic practices sometimes result in higher concentrations of phenolics (e.g. flavonoids) and antioxidant activity than their conventional counterparts. There are limited data though and a lack of evidence to more broadly understand impacts and draw firm conclusions.

- For organically grown crops there is a greater body of research comparing organic and conventionally grown crops. There appears to be limited impact of organic practices on macronutrients but some evidence of impact on selected micronutrients (e.g. vitamin C) and more evidence for increasing concentrations of phenolics.

- Conventional crops have consistently been shown to have higher pesticide concentrations and higher nitrate concentrations than those grown organically (there are fewer studies with biodynamic crops but expectations they would confer the same advantage as organic).

- Organic and biodynamic systems are likely to supply different amounts of elements compared to conventional systems. In particular, some amounts of trace elements are higher in the compost and manures applied by organic and biodynamic growers compared to the lime and N:P:K fertilisers used in conventional farming. Understanding the input of nutrients and the relationship with plant composition will help guide and potential improve future practices.

- There is evidence in the literature that elevated soil health, which includes aspects such as elevated soil organic matter (SOM) and functionally healthy microbial biomass allow plants to perform better physiologically with greater resilience to stress, meaning they have better chance to adsorb the nutrients they need to thrive. This leads to a state of 'improved nutrient density' overall. Understanding exactly which biodynamic practices deliver improved soil health will potentially help drive improvements in nutrient density/crop composition.

- Aspects of biodynamic and organic agriculture that resonate most with consumers convey messages about soil, water, and biodiversity, with the influence of this production system on taste and consumers' personal health also being important. There are few studies on consumers' understanding and perceptions of the term 'nutrient density' and thus there may be a risk in using 'nutrient density' in communicating about the advantages of biodynamic agriculture. This needs further exploration as to how and what to convey.

Overall, there are large gaps in the research when it comes to understanding the impacts of biodynamic growing practices on the composition, health benefits and sensory properties of foods, particularly in a New Zealand context. Even when comparing organic and conventionally grown produce, the evidence of an advantage for organics is variable. In both cases there is some evidence of an advantage for both biodynamics and organic, particularly around an increase in phytochemicals, but it is not consistent and there is a lack of multiple studies on the same crop. Thus, there is considerable potential for further research to build the evidence base. The next steps for the project are to further refine what may be required in a future study.

The second phase of the project will develop a work plan that will aim to fill in the gaps of the existing knowledge base, focusing on the use of field work and consumer insights research. This work plan will be converted into a funding proposal targeting MPI's SFFF or similar.

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Appendix 1. Key nutrients for human health and recommended intakes

Daily reference values for core nutrients specified in FSANZ Standard 1.2.8 (Food Standards Australia New Zealand 2021)

Food component	Units	Reference value
Energy	kJ	8700
Protein	g	50
Fat	g	70
Saturated fatty acids	g	24
Carbohydrate	g	310
Sodium	mg	2300
Sugars	g	90
Dietary fibre (if included)	g	30

Vitamins and minerals specified in FSANZ Schedule 1 and their thresholds for nutrient content claims (Food Standards Australia New Zealand 2018a).

Nutrient	Units	Adult	RDI or ESADDI	Source	Good source
Biotin	µg	30	ESADDI	3	7.5
Folate	µg	200	RDI	20	50
Niacin	mg	10	RDI	1	2.5
Pantothenic acid	mg	5	ESADDI	0.5	1.25
Riboflavin (vitamin B2)	mg	1.7	RDI	0.17	0.43
Thiamin (vitamin B1)	mg	1.1	RDI	0.11	0.28
Vitamin A	µg	750	RDI	75	188
Vitamin B6	mg	1.6	RDI	0.16	0.4
Vitamin B12	µg	2	RDI	0.2	0.5
Vitamin C	mg	40	RDI	4	10
Vitamin D	µg	10	RDI	1	2.5
Vitamin E	mg	10	RDI	1	2.5
Vitamin K	µg	80	ESADDI	8	20
Calcium	mg	800	RDI	80	200
Chromium	µg	200	ESADDI	20	50
Copper	mg	3	ESADDI	0.3	0.75
Iodine	µg	150	RDI	15	37.5
Iron	mg	12	RDI	1.2	3
Magnesium	mg	320	RDI	32	80
Manganese	mg	5	ESADDI	0.5	1.25
Molybdenum	µg	250	ESADDI	25	62.5
Phosphorus	mg	1000	RDI	100	250
Selenium	µg	70	RDI	7	17.5
Zinc	mg	12	RDI	1.2	3

Abbreviations: ESADDI = estimated safe and adequate daily dietary; RDI = recommended dietary intake.

Some of the other nutrient thresholds specified in FSANZ Standard 1.2.7 (Food Standards Australia New Zealand 2018b) and Schedule 4 for claims (Food Standards Australia New Zealand 2023)..

Nutrient	Claimable amount
Dietary fibre	≥2 g/serve = source; ≥4 g/serve = good source; ≥7 g/serve = excellent source
Protein	≥5 g per serve = source; ≥4 g/serve = good source
Potassium	≥200 mg per serve
Carbohydrate (for energy)	carbohydrate must contribute 55% of the energy content
Energy (for contributing energy for normal metabolism)	≥420kJ per serve
Fat (low)	≤3 g per 100 g for solid food
Monounsaturated fatty acids	The food contains, as a proportion of the total fatty acid content: (a) no more than 28% saturated fatty acids and trans fatty acids; and (b) no less than 40% monounsaturated fatty acids.
Omega-3 fatty acids	≥200 mg alpha-linolenic/serve or ≥30 mg total eicosapentaenoic acid and docosahexaenoic acid /serve = source; ≥60 mg total eicosapentaenoic acid and docosahexaenoic acid /serve = source = good source
Sodium/salt (low)	≤120 mg per 100 g

Appendix 2. Well-established health benefits of nutrients

Pre-approved health claims for nutrients under FSANZ regulations (Food Standards Australia New Zealand 2023). Claims are general level unless otherwise specified.

Nutrient	Health effect	Map to generic health area
Carbohydrate	Contributes energy for normal metabolism	Energy & metabolism
Protein	Necessary for tissue building and repair	Cell & tissue growth
	Necessary for normal growth and development of bone in children (4 yr+)	Growth & development in children
	Contributes to the growth of muscle mass	Physical performance
	Contributes to the maintenance of muscle mass	Physical performance
	Contributes to the maintenance of normal bones	Bone health
	Necessary for normal growth and development in children (4 yr+)	Growth & development in children
Dietary Fibre	Contributes to regular laxation	Digestive health
Biotin	Contributes to normal fat metabolism and energy production	Energy & metabolism
	Contributes to normal functioning of the nervous system	Brain and nervous system
	Contributes to normal macronutrient metabolism	Energy & metabolism
	Contributes to normal psychological function	Brain and nervous system
	Contributes to maintenance of normal hair	Hair & nails
	Contributes to maintenance of normal skin and mucous membranes	Skin
Choline	Contributes to normal homocysteine metabolism	Energy & metabolism
	Contributes to normal fat metabolism	Energy & metabolism
	Contributes to the maintenance of normal liver function	Liver health
Folate[a]	Necessary for normal blood formation	Heart & circulation
	Necessary for normal cell division	Cell & tissue growth
	Contributes to normal growth and development in children	Growth & development in children
	Contributes to maternal tissue growth during pregnancy	Pregnancy
	Contributes to normal amino acid synthesis	Cell & tissue growth
	Contributes to normal homocysteine metabolism	Heart & circulation
	Contributes to normal psychological function	Brain and nervous system
	Contributes to normal immune system function	Immune function & inflammation
	Contributes to the reduction of tiredness and fatigue	Tiredness & fatigue
Niacin (B3)	Necessary for normal neurological function	Brain and nervous system
	Necessary for normal energy release from food	Energy & metabolism
	Necessary for normal structure and function of skin and mucous membranes	Skin
	Contributes to normal growth and development in children	Growth & development in children
	Contributes to normal psychological function	Brain and nervous system
	Contributes to the reduction of tiredness and fatigue	Tiredness & fatigue
Pantothenic acid	Necessary for normal fat metabolism	Energy & metabolism
	Contributes to normal growth and development in children	Growth & development in children

Nutrient	Health effect	Map to generic health area
	Contributes to normal energy production	Energy & metabolism
	Contributes to normal mental performance	Brain and nervous system
	Contributes to normal synthesis and metabolism of steroid hormones, vitamin D and some neurotransmitters	Hormonal function
	Contributes to the reduction of tiredness and fatigue	Tiredness & fatigue
Riboflavin (B2)	Contributes to normal iron transport and metabolism	Energy & metabolism
	Contributes to normal energy release from food	Energy & metabolism
	Contributes to normal skin and mucous membrane structure and function	Skin
	Contributes to normal growth and development in children	Growth & development in children
	Contributes to normal functioning of the nervous system	Brain and nervous system
	Contributes to the maintenance of normal red blood cells	Heart & circulation
	Contributes to the maintenance of normal vision	Eye health
	Contributes to the protection of cells from oxidative stress	Prevention oxidative damage (antioxidant)
	Contributes to the reduction of tiredness and fatigue	Tiredness & fatigue
Thiamin (B1)	Necessary for normal carbohydrate metabolism	Energy & metabolism
	Necessary for normal neurological and cardiac function	Brain and nervous system; Heart & circulation
	Contributes to normal growth and development in children	Growth & development in children
	Contributes to normal energy production	Energy & metabolism
	Contributes to normal psychological function	Brain and nervous system
Vitamin A	Necessary for normal vision	Eye health
	Necessary for normal skin and mucous membrane structure and function	Skin
	Necessary for normal cell differentiation	Cell & tissue growth
	Contributes to normal growth and development in children	Growth & development in children
	Contributes to normal iron metabolism	Energy & metabolism
	Contributes to normal immune system function	Immune function & inflammation
Vitamin B6	Necessary for normal protein metabolism	Energy & metabolism
	Necessary for normal iron transport and metabolism	Energy & metabolism
	Contributes to normal growth and development in children	Growth & development in children
	Contributes to normal cysteine synthesis	Energy & metabolism
	Contributes to normal energy metabolism	Energy & metabolism
	Contributes to normal functioning of the nervous system	Brain and nervous system
	Contributes to normal homocysteine metabolism	Heart & circulation
	Contributes to normal glycogen metabolism	Energy & metabolism
	Contributes to normal psychological function	Brain and nervous system
	Contributes to normal red blood cell formation	Heart & circulation
	Contributes to normal immune system function	Immune function & inflammation
	Contributes to the reduction of tiredness and fatigue	Tiredness & fatigue
	Contributes to the regulation of hormonal activity	Hormonal function

Nutrient	Health effect	Map to generic health area
Vitamin B12	Necessary for normal cell division	Cell & tissue growth
	Contributes to normal blood formation	Heart & circulation
	Necessary for normal neurological structure and function	Brain and nervous system
	Contributes to normal growth and development in children	Growth & development in children
	Contributes to normal energy metabolism	Energy & metabolism
	Contributes to normal homocysteine metabolism	Heart & circulation
	Contributes to normal psychological function	Brain and nervous system
	Contributes to normal immune system function	Immune function & inflammation
	Contributes to the reduction of tiredness and fatigue	Tiredness & fatigue
Vitamin C	Contributes to iron absorption from food	Energy & metabolism
	Necessary for normal connective tissue structure and function	Joint health; Cell & tissue growth; Bone health
	Necessary for normal blood vessel structure and function	Heart & circulation
	Contributes to cell protection from free radical damage	Prevention oxidative damage (antioxidant)
	Necessary for normal neurological function	Brain and nervous system
	Contributes to normal growth and development in children	Growth & development in children
	Contributes to normal collagen formation for the normal structure of cartilage	Joint health
	Contributes to normal collagen formation for the normal structure of bones	Bone health
	Contributes to normal collagen formation for the normal function of teeth	Oral health
	Contributes to normal collagen formation for the normal function of gums	Oral health
	Contributes to normal collagen formation for the normal function of skin	Skin
	Contributes to normal energy metabolism	Energy & metabolism
	Contributes to normal psychological function	Brain and nervous system
	Contributes to the normal immune system function	Immune function & inflammation
	Contributes to the reduction of tiredness and fatigue	Tiredness & fatigue
Vitamin D	Necessary for normal absorption and utilisation of calcium and phosphorus	Bone health
	Contributes to normal cell division	Cell & tissue growth
	Necessary for normal bone structure	Bone health
	Contributes to normal growth and development in children	Growth & development in children
	Contributes to normal blood calcium levels	Energy & metabolism
	Contributes to the maintenance of normal muscle function	Physical performance
	Contributes to the maintenance of normal teeth	Oral health
	Contributes to the normal function of the immune system	Immune function & inflammation
Vitamin E	Contributes to cell protection from free radical damage	Prevention oxidative damage (antioxidant)
	Contributes to normal growth and development in children	Growth & development in children
Vitamin K	Necessary for normal blood coagulation	Heart & circulation

Nutrient	Health effect	Map to generic health area
	Contributes to normal bone structure	Bone health
	Contributes to normal growth and development in children	Growth & development in children
Calcium	Enhances bone mineral density (high level)	Bone health
	Reduces risk of osteoporosis in people over 65 (high level)	Bone health
	Reduces risk of osteoporotic fracture in people over 65 (high level)	Bone health
	Necessary for normal teeth and bone structure	Bone health; Oral health
	Necessary for normal nerve and muscle function	Brain and nervous system; Physical performance
	Necessary for normal blood coagulation	Heart & circulation
	Contributes to normal energy metabolism	Energy & metabolism
	Contributes to the normal function of digestive enzymes	Digestive health
	Contributes to normal cell division	Cell & tissue growth
	Contributes to normal growth and development in children	Growth & development in children
Chromium	Contributes to normal macronutrient metabolism	Energy & metabolism
Copper	Contributes to normal connective tissue structure	Joint health; Cell & tissue growth; Bone health
	Contributes to normal iron transport and metabolism	Energy & metabolism
	Contributes to cell protection from free radical damage	Prevention oxidative damage (antioxidant)
	Necessary for normal energy production	Energy & metabolism
	Necessary for normal neurological function	Brain and nervous system
	Necessary for normal immune system function	Immune function & inflammation
	Necessary for normal skin and hair colouration	Skin; Hair & nails
	Contributes to normal growth and development in children	Growth & development in children
Fluoride	Contributes to the maintenance of tooth mineralisation	Oral health
Iodine	Necessary for normal production of thyroid hormones	Hormonal function
	Necessary for normal neurological function	Brain and nervous system
	Necessary for normal energy metabolism	Energy & metabolism
	Contributes to normal cognitive function	Brain and nervous system
	Contributes to the maintenance of normal skin	Skin
	Contributes to normal growth and development in children	Growth & development in children
Iron	Necessary for normal oxygen transport	Heart & circulation
	Contributes to normal energy production	Energy & metabolism
	Necessary for normal immune system function	Immune function & inflammation
	Contributes to normal blood formation	Heart & circulation
	Necessary for normal neurological development in the foetus	Pregnancy
	Contributes to normal cognitive function	Brain and nervous system
	Contributes to the reduction of tiredness and fatigue	Tiredness & fatigue
	Necessary for normal cell division	Cell & tissue growth
	Contributes to normal growth and development in children	Growth & development in children

Nutrient	Health effect	Map to generic health area
	Contributes to normal cognitive development in children	Growth & development in children
Magnesium	Contributes to normal energy metabolism	Energy & metabolism
	Necessary for normal electrolyte balance	Hydration
	Necessary for normal nerve and muscle function	Brain and nervous system; Physical performance
	Necessary for teeth and bone structure	Bone health; Oral health
	Contributes to a reduction of tiredness and fatigue	Tiredness & fatigue
	Necessary for normal protein synthesis	Energy & metabolism
	Contributes to normal psychological function	Brain and nervous system
	Necessary for normal cell division	Cell & tissue growth
	Contributes to normal growth and development in children	Growth & development in children
Manganese	Contributes to normal bone formation	Bone health
	Contributes to normal energy metabolism	Energy & metabolism
	Contributes to cell protection from free radical damage	Prevention oxidative damage (antioxidant)
	Contributes to normal connective tissue structure	Joint health; Cell & tissue growth; Bone health
	Contributes to normal growth and development in children	Growth & development in children
Molybdenum	Contributes to normal sulphur amino acid metabolism	Energy & metabolism
Phosphorus	Necessary for normal teeth and bone structure	Bone health; Oral health
	Necessary for the normal cell membrane structure	Cell & tissue growth
	Necessary for normal energy metabolism	Energy & metabolism
	Contributes to normal growth and development in children	Growth & development in children
Potassium	Necessary for normal water and electrolyte balance	Hydration
	Contributes to normal growth and development in children	Growth & development in children
	Contributes to normal functioning of the nervous system	Brain and nervous system
	Contributes to normal muscle function	Physical performance
Selenium	Necessary for normal immune system function	Immune function & inflammation
	Necessary for the normal utilisation of iodine in the production of thyroid hormones	Hormonal function
	Necessary for cell protection from some types of free radical damage	Prevention oxidative damage (antioxidant)
	Contributes to normal sperm production	Reproductive health
	Contributes to the maintenance of normal hair and nails	Hair & nails
	Contributes to normal growth and development in children	Growth & development in children
Sodium	Diet low in salt or sodium reduces blood pressure	Heart & circulation
Zinc	Necessary for normal immune system function	Immune function & inflammation
	Necessary for normal cell division	Cell & tissue growth
	Contributes to normal skin structure and wound healing	Skin
	Contributes to normal growth and development in children	Growth & development in children
	Contributes to normal acid-base metabolism	Energy & metabolism

Nutrient	Health effect	Map to generic health area
	Contributes to normal carbohydrate metabolism	Energy & metabolism
	Contributes to normal cognitive function	Brain and nervous system
	Contributes to normal fertility and reproduction	Reproductive health
	Contributes to normal macronutrient metabolism	Energy & metabolism
	Contributes to normal metabolism of fatty acids	Energy & metabolism
	Contributes to normal metabolism of vitamin A	Energy & metabolism
	Contributes to normal protein synthesis	Cell & tissue growth
	Contributes to the maintenance of normal bones	Bone health
	Contributes to the maintenance of normal hair and nails	Hair & nails
	Contributes to the maintenance of normal testosterone levels in the blood	Reproductive health
	Contributes to cell protection from free radicals	Prevention oxidative damage (antioxidant)
	Contributes to the maintenance of normal vision	Eye health
Beta-glucan	Reduces blood cholesterol (high level)	Heart & circulation
	Reduces dietary and biliary cholesterol absorption	Heart & circulation
Calcium and vitamin D	Reduces risk of osteoporosis in people over 65 (high level)	Bone health
	Reduces risk of osteoporotic fracture in people over 65 (high level)	Bone health
Phytosterols, phytostanols and their esters	Reduces blood cholesterol (high level)	Heart & circulation

[a] Note this is claims for naturally occurring folates and does not include claims for folic acid (this is not included as is the synthetic form so not present in crops).

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