I. THIRTEEN ECONOMIC VALUE PROPOSITIONS

The diagram maps the relationship between farm practices and economic value propositions. This section of notes introduces economic aspects of each value proposition listed, including a brief summary of who in society might value it, and why.

As summarized below, these values can play out in economics through payments to farmers for conservation of ecosystems, wildlife, or pollinators (either on a case-by-case basis or through programs like biodiversity offset trading); product differentiation in marketing to consumers; increased revenue to the farm and community through tourism; the various benefits of soil health and landscape resiliency that biodiversity tends to support; welfare and productivity of farm workers; volunteer and local political support for certain farming practices; and in other ways.

The diagram clearly shows that each farm practice affects multiple potential values, and that many of these are not only inter-related but inseparable from the perspective of the underlying science. This is an essential point: these are systemic connections, and nearly every farm action that affects one aspect also impacts other, whether those are recognized and valued or not.

The term “value propositions” is used rather than “values” because, while each item listed in the diagram and these notes reflects actual initiatives and enterprises, many are not standardized across society. These are opportunities that are not yet being taken advantage of by a lot of people. In many cases, these are acted upon only on a case-by-case basis. They are “propositions” for a great many others, connecting with both consumers’ and producers’ willingness to spend money, time, or other resources for the affected farming, health, social, and environmental consequences.

Of note, changes in the farm practices listed may have positive or negative impact on these value propositions. In some cases, a farm practices that increases one type of value may decrease others, such as a practice that increases yield of a crop as defined by its bulk weight or volume but, at the same time, decreases the crop’s nutritional quality, soil health, or ecosystem conditions affecting other values.

This section provides brief introductions to the thirteen factors identified as valuable to some people in society, and as tangible value propositions to others.

1. Health quality of food

This assessment focuses on farming practices that can affect the nutritional characteristics of foods. It does not address the many other complex relationships between food and human health that take place after a product leaves the farm. As listed in the diagram, distinct nutritional qualities that may be affected by farming practices include conventional nutrients (i.e. proteins, carbohydrates, vitamins, minerals, fats), dietary fiber, secondary compounds/phytonutrients, dietary impacts on gut microbiome, calories, and toxicity. These can affect a person's health directly and in relationship to each other, such as calories or certain minerals relative to other nutrients consumed. Some of these factors also vary based on the individual's ethnicity, age, gender, and other health conditions. Amid this complexity, three factors of particular interest emerge in this mapping of inter-related factors on the farm and value propositions linked to farming practices. These will also be discussed more in section III about the different farm practices.

- Micronutrients: How the relationship between seed types (genetics) and particular soil qualities (including microbial and fungal content) affects the uptake of less-soluble micronutrients like iron and zinc from the soil into the plants. Conventionally managed soils tend to lack both the soil microbial life and crops with this nutrient-accessing ability. Plant varieties that have been bred for use with chemical fertilizers and pesticides have often lost the ability to forge the microbial partnerships to meet these nutrient needs.
- Phytonutrients such as polyphenols and various types of antioxidants: These kinds of nutrients can affect chronic diseases, inflammation, gut health, and other conditions, but aren't listed on most food labels. Some phytonutrients are absorbed directly into the human body, while others support digestive, immune, endocrine, and metabolic systems in other ways. Plants produce these phytonutrients as part of their own immune systems and in response to environmental stresses in soils and surrounding ecosystems. Stresses can include insects, microbes, fungi, other plants, and non-biological factors like weather conditions. Chemical and mechanical approaches to defeat pests in conventional farming often alleviate the need for plants to develop their own defense systems involving phytonutrients.
- Fatty acid composition in meat, dairy, and eggs: Recent studies show that animals that graze on bio-diverse pastures tend to have higher levels of largely good, anti-inflammatory omega-3s, lower levels of often-inflammatory omega-6s, and increased conjugated linoleic acid (CLA), a healthy antioxidant with anti-inflammatory properties.

Of course, any farming practices that introduce harmful levels or types of toxins from chemical pesticides, fertilizers, or other sources would also affect health directly, in addition to their impact on some nutrient stimulants in soils and surrounding ecosystems.

2. Standardized shape, color & size of product

Commercial crops are often grown to produce a "standardized" look and feel of food products, such as a typical color and size of carrots or tomatoes or chickens. These are intended either to appeal to consumer expectations in the marketplace, or to meet the requirements of commercial food processing or farm harvesting equipment that has been engineered to work efficiently with a specific size and shape of product. Buyers have also prioritized shelf-life of products, high test weight, and protein content and certain baking qualities in grains. Farmer and food company prioritization of standardized crops like this, while creating tremendous efficiencies and some other benefits, is also attributed with some of the loss over time of vegetable diversity, nutrition, flavor and other food quality attributes.

3. Aroma or flavor of food

Freshness, nutritional compounds, and genetics affect the flavor, aroma and texture of foods. People with pride in their cooking and traditions, such as many professional chefs, neighborhood bakers, grandmothers serving their families, and people serving friends, value these qualities in their ingredients and recipes. These food qualities play a strong role in ethnic and family traditions and celebrations as well, with social and cultural importance and health implications reaching beyond just the flavor. For example, national award-winning chef Dan Barber is known for focusing his restaurants on specific relationships between food's "deliciousness" and organic growing practices on the farm, and recent James Beard and Julia Child awards winner Sean Sherman, known as The Sioux Chef, procures indigenous heritage and natural varieties of corn specifically for the texture qualities they give tortillas and their use in culturally important products. These kinds of factors, i.e. the products and their socialization by food influencers in families and society, can affect demand for particular varieties, ingredients grown in particular conditions, and those with particular cultural resonance. This is also addressed in the points below on the economic power of community and cultural values, and the historical health benefits at the center of some cultural food traditions.

4. Climate change mitigation (GHG/carbon)

A great deal of attention and resources are being invested in the relationship between agriculture, emission of greenhouse gases like carbon dioxide and methane into the atmosphere, greenhouse gas sequestration from the atmosphere into plants and soils, and the impact of increased atmospheric carbon on plant growth and nutrition. Carbon credit trading initiatives focus on rewarding farmers and others for reducing greenhouse gases in the atmosphere, including through soils and in some innovative approaches that use farmer incentives through carbon payments to reduce destruction of surrounding biodiversity and forests, such as the organic food products company COMACO that rewards more than 250,000 farmers with annual cash dividends.

5. Biodiversity value

Different segments of society value the local and regional mix of plants, wildlife, and natural ecology for many distinct reasons. Farming practices affect these directly. This includes biodiversity above ground in forests, waterways, and farmlands, and biodiversity below ground in soils. The social and economic importance of these topics is reflected in the current development of international biodiversity conservation protocols being facilitated with the United Nations and others. People increasingly place value on the role plants, animals, and microbes play in fostering healthy soils and thus supporting resilient landscapes; biodiversity's role in stimulating phytonutrient production in plants; natural ways of controlling pests based on fostering rich ecosystems rather than killing unwanted plants and animals with chemicals; support for pollinators and other beneficial insects; biodiversity's role in fostering genetic diversity and thus evolution and disease resistance; the attraction of natural farmscapes and landscapes to tourists who bring additional resources to a community; a reverence for the intrinsic value of nature as revealed in some of society's most influential poetry, philosophy, and religious traditions; and beliefs in some cultures that relationships with other forms of life are sacred. These values can play out in economics through payments to farmers for conservation of ecosystems, wildlife, or pollinators (either on a case-by-case basis or through programs like biodiversity offset trading); product differentiation in marketing to consumers; increased revenue to the farm and community through tourism; the various soil health and landscape resiliency benefits that biodiversity tends to support; welfare and productivity of farm workers; volunteer and local political support for certain farming practices; and in other ways.

6. Local landscape resiliency to disruption/disaster

The recovery of land, vegetation, wildlife and water systems are of vital importance following local and regional natural disasters. For example, how natural ecosystems bounce back or adapt after a wildfire, flood, drought, or extreme heat or cold affects community health, economic activity, natural resources, and much more. Organic characteristics in soils help mitigate the magnitude of damage and fuel a faster recovery. This includes, for example, tree roots, biochar, and fungi providing habitat and holding structure, nutrients, and seeds that support both short-term and longer-term re-growth. Factors that foster such resiliency and regrowth are of value to communities, municipalities, private land holders who have long-term interest in the property, and organizations that absorb costs of disasters including insurance companies, financial institutions in the region, and state and federal government agencies.

7. Local food system resiliency to disruption/disaster

The need to mitigate shocks to food and nutrition in the face of natural disasters, disease outbreaks, war and conflict, or other disruptions is garnering increased attention among communities, families, and state and national governments. For example, the COVID-19 pandemic caused farmworker shortages, food factory shut-downs, supply chain disruptions for grocery stores, further drops in fresh and nutritional foods in marginalized urban and rural communities, and spikes in demand at local food banks. Food prices also increased substantially. Solutions in some areas support diversifying local food production (farming) to assure more redundancy and some degree of local self-sufficiency as well as adequate nutrition during crises; locally operated food hubs and other community-based resources and communications channels rather than dependence solely on government-, corporate-, or market-controlled approaches; and farmers focusing on soil and ecosystem health and perennial crops in some areas so their production withstands or bounces back from shocks more effectively.

8. Water quality and quantity (regional hydrology)

Farming and water affect each other in a great many ways, through water consumption and conservation practices, impact of watersheds and groundwater (both at the farm's source and downstream), water requirements of crops selected for production, related irrigation infrastructure, pollution, and otherwise. Vegetation in a landscape also affects weather and rain patterns in some geographies. This can affect both local/small and regional/large water cycles. Some of these focus on the water itself, others focus on land practices that are interdependent with water cycles such as managing soil qualities and vegetation around the farm (including trees, hedgerows, fallow fields, terrain and wetlands bordering streams and lakes, etc.). Direct impacts include quantity of product grown per crop cycle; number of crops cycles per year; watershed and groundwater replenishment or depletion in the surrounding area; impacts of runoff of soil, nutrients, and chemicals; wildlife habitat on or near the farm site; downstream water quality and quantity (both locally and long distances away); cultural connections to water in some communities; legal water rights; and impact of all these factors on local food system resiliency and landscape resiliency. Plentiful, though sometimes complicated, action opportunities and value creation result from these many relationships between farmers and other water interests in the public and private sectors.

9. Pollinator health

Bees and other insects that pollinate plants are important in agricultural success, and of course to forests, fields, and flower gardens more broadly. Whether in a landscape year-round or brought in to pollinate or make honey on a temporary basis, bees create immense value for farmers and for society in general. Innovative new science also opens the door to other services bees can provide, such as the work of the company BeeOdiversity that provides farmers, companies, and governments with precise biodiversity and pollutant data in a region by analyzing statistically rigorous samples of plant pollens collected by bees across the surrounding countryside. The bees that offer these pollination and data services can also be harmed when the number or diversity of flowering plants is reduced and when particular types or mixes of pesticides are used during pollinator-sensitive times of the day or year. Initiatives focused on helping farmers, consumers, and companies realize more of the value potential of pollinators include pollinator-friendly food labels that reflect farming practices; inclusion of pollinators in ecosystem services payments programs; and practical biodiversity impact metrics, measurement, and reporting tools and protocols.

10. Community and cultural values, relationships

A person's culture can influence food choices and farming practices in powerful ways. Culture is a powerful motivator for some ingredients, recipes, and growing or harvesting techniques. This includes connections to food and farming through family, ethnic, community, and religious histories and traditions, such as foods prevalent during someone's childhood (which are often connected emotionally with parents or grandparents); foods celebrated during holidays; foods reflecting the geography where someone lived; the types of "comfort foods" people like to eat when not feeling well; natural healing qualities people believe in; family bonds formed around gardening or fishing, hunting, or harvesting in other ways; and traditional land or ecosystem stewardship practices that people value for their ritual as much as for their direct impact on the land and foods. This economic force also includes connections to environmental themes that motivate some groups of people, such as impact on wild animals, animal welfare in general, nature, and water systems. The nutritional roots of some of these same personal and cultural values are also interesting to consider, whether or not the modern-day community realizes those historical connections. For example, some community celebrations emphasize foods and harvesting techniques that historically provided nutrition through the changing seasons or that connected with people's sovereignty over their own ways of life. All of these factors can correlate with both consumers' and producers' willingness to spend money, time, or political action for a particular product or supporting certain farming, environmental, and community practices.

11. Reduced pollution (in soil, water, and air)

In addition to potential benefits to ecology and human health, reducing pollution can provide direct value to the farm and food producer. Pollution reversed for benefits might include, for example, runoff of excess nutrients such as phosphorus into waterways (with positive impact on fish and wildlife and reduced monitoring or disposal costs), chemical drift through the air or into water or soils, impact on pollinators, and disposal of food processing “wastes” through site-specific or municipal waste treatment systems. Benefits might come in several forms:

- Reduced costs, such as paying lower disposal, regulatory, or monitoring fees, or the cost of managing community relationships linked to pollution issues;
- Direct revenue, for value created for example by reusing products that formerly polluted (such recycling your crop into phosphorus-rich fertilizers), or pollinator stewardship funds received in exchange for reducing certain pesticide applications;
- Non-monetary benefits such as realizing increases in natural pollination on a farm, or positive publicity value of reducing pollution.

12. Farm worker health and safety

Farm workers are known to be affected physically and mentally by on-farm working conditions, some of which overlap with factors that affect quality of the food grown, as detailed throughout this assessment. Documented conditions affecting farmworker health and safety include exposure to diverse microbiomes in the soils in which they work, risks of exposure to harmful waste or chemicals, and mental and productivity benefits of working in an environment including a diversity of plants and animals. Farmworker health is of course important to the individual, families, and communities, and usually to employers who seek a positive work environment, worker productivity, employee retention over time, skills development, and positive public and marketing recognition. Farmworker health is also important to government labor regulators and labor rights advocates. Furthermore, as economic values flowing from organic and regenerative practices continue to increase — fueled by the economics highlighted throughout this assessment — hands-on workers who understand regenerative crop growing techniques and the nuances of organic soil quality seem likely to become increasingly valuable to the farm as well.

13. Increased land value

Depending on a potential buyer’s or underwriter’s interests, farming practices can affect the market value of the land itself. Relevant factors include impact on soil quality or perennial crops for future farming, resiliency of the land in the face of shifting weather patterns, carbon retention in the soil and surrounding ecosystem, increasing the nutritional value of food crops grown on that land, biodiversity characteristics for environmental or perceived ESG or MRV value, recreational or tourism value of the property, cultural value in the region, and probably more. All of these will probably continue to shift over time as nutrient cycling and regenerative farming are increasingly recognized and mainstreamed in society.

II. SIX ON-FARM DETERMINANTS OF FOOD QUALITY

The diagram illustrates how practices chosen by farmers affect economic value propositions for themselves and others. The diagram also illustrates the scientific relationship between many of those practices.

This section of notes is intended primarily as a reference tool to support the diagram. It provides a brief overview of each of the forty-six farm practices, including a description, the underlying science of how it works, and its interrelationships with other scientific or economic factors.

The practices are organized into the six major categories listed on the diagram: (1) Initial seed/plant/animal selection, (2) Soil health (biological/chemical/physical; microbes & fungi, organic matter, (3) Ecosystem interdependence around the farm, (4) Plant or animal management practices, (5) Post-harvest crop management, and (6) Compounds that can be harmful to humans.

1. Initial seed/plant/animal selection

- *1a. Baseline nutritional profile of the crop or animal*
- *1b. Varietal/breed*
- *1c. Genetics*
  - *1ci. Heritage Varieties*
  - *1cii. Hybrid Varieties*
  - *1ciii. GMO – Genetically Modified Organisms*
  - *1civ. Biofortified*
  - *1cv. Regional*
- *1d. Seed management*
  - *1di. Organic seeds*
  - *1dii. Microbial seed treatment before planting*
- *1e. Congruence with regional weather/pest/ecosystem conditions*

1a. Baseline nutritional profile of the crop or animal

Every crop or animal product starts with its own basic nutritional profile, which can then be affected by other factors summarized in this note. For example, and obviously, tomatoes are nutritionally different from blueberries, which are different from beef, which is different from oats, etc. This variation is found across several aspects of nutrition, including vitamins, minerals, proteins, carbohydrates, fats, fiber, calories, and phytonutrients.

Certain nutritional characteristics stand out in some types of products. For example, carrots are known as an excellent source of vitamin A. Blueberries tend to be high in a type of phytonutrients called anthocyanins (a flavonoid), while tomatoes are high in lycopene (a terpenoid). Animal proteins contain all nine essential amino acids that human bodies need, while plant proteins generally do not contain all nine amino acids in one source. Certain other nutrients are unique or more abundant in animals compared to plants, such as the important antioxidant *conjugated linoleic acid* (CLA), a fatty acid found primarily in meat and dairy of animals that are ruminants.

Health characteristics related to a nutrient can also vary depending on its specific source. For example, heme iron, found only in meat, fish, and poultry, is more bioavailable (better absorbed and utilized) than plant sources of iron. Additionally, nutrient bioavailability can also be dependent on the availability of other nutrients and the food's form or structure.

1b. Varietal/breed

The particular varietal of a crop or breed of an animal can further affect its basic nutritional profile. This refers to differences within a particular species, such as differences between types of carrots, or between types of cattle. Some nutrients and phytonutrient levels inherent to a species may nevertheless vary within its varietals. Crop varietal has also been shown to affect bioavailability, and whether micronutrients concentrate or relocalize into the part of the crop eaten by humans, such as the leaf, root, fruit, or seed. Similarly, different animal breeds of the same species produce different kinds of proteins: For example, A2/A2 beta-casein protein is known to be easier for humans to digest and absorb compared to A1/A1 or A1/A2 beta-casein (the genetics in most US dairies), which has been linked to some cases of inflammation and gut discomfort.

Of particular note for this economics assessment, farmers often choose to grow varietals and breeds for reasons other than nutrition, such as their color, consistency, ability to grow in dry or wet conditions, pest resistance, request of their market buyers, initial seed or animal availability and price, their (or their neighbor's) success with that species or varietal in past years, or for other reasons. But their choice, regardless of reason, often intersects with nutrition as well. As another example, certain cattle breeds have traits that make them preferred for rotational or nomadic grazing methods: the cattle are relatively small, wide-bodied, with strong feet and legs that allow them to travel greater distances. And per section (**4g**) about livestock feed, this ends up affecting the nutritional qualities of the resulting beef as well.

1c. Genetics

The genetics of a plant or animal affects its nutrition, whether intentionally or not.

1ci. Heritage Varieties

Heritage seeds are in a persistent natural state. While they evolved and may have been selectively bred over time, they have not been engineered *per se* by breeders or lab scientists. These crops are often adapted naturally to specific environmental conditions in which they evolved originally (soils, weather, etc.) Heritage varieties have been shown to have greater colonization and symbiosis of beneficial mycorrhizal fungi with their roots in certain growing conditions, and therefore better able to access nutrients in the soil, compared to commercial hybrids which are often adapted or designed specifically for nutrients through fertilization. Heritage varieties can also produce more phytonutrients than hybridized or genetically modified varieties, because they have not lost phytonutrient traits through selective breeding for factors such as sweet or mild flavors, and related marketing reasons; some beneficial phytonutrients have a strong taste (bitter, astringent, or sour), which appeals to some people and in some traditional and cultural foods and recipes, but may not taste as appealing to others.

1cii. Hybrid Varieties

Produced by crossbreeding multiple varieties, seeds and animals have been hybridized since the advent of industrial agriculture to produce various benefits: greater yield, larger size, resistance to disease, longer shelf life, the ability to store and ship well, crop uniformity, flavors that appeal more to some consumers, and for other reasons. Such seeds often produce larger crops, but do not develop more expansive root systems, so micronutrients absorbed from the soil are spread thinner in the plant, creating what has come to be known as the *genetics-driven dilution effect*. Additionally, when such seeds are bred to be productive using high levels of synthetic nitrogen and other fertilizers, as with many modern commercial crops, they often do not perform well in natural or organic growing conditions that don’t use such fertilizers.

1ciii. GMO – Genetically Modified Organisms

Genetically modifying the DNA of a seed or animal in a laboratory affects subsequent growing practices and product characteristics, some intentionally and some not. For example, genetic modification has been used to change plants’ growth rates, pest resistance, weather and environmental conditions (drought, flood, heat, or cold tolerance), isolated nutritional qualities, dependence on specific fertilizers or other pesticides, ability to reproduce, and more. These modifications may also affect food quality and other prospective economic values of farming as identified in this assessment. This can happen directly (such as increasing the vitamin A production in sweet potatoes used in a particular region) and indirectly (such as genetically-engineered corn or soybean resistance to the herbicide glyphosate leading to widespread use that has arguably lowered farming's financial costs in the near term while also degrading soil life and biodiversity).

1civ. Biofortified

Biofortification is the process of increasing the content and/or bioavailability of certain nutrients in crops. Seeds can be biofortified through plant-breeding or genetic modification (GMO). Biofortification has primarily focused on starchy staple crops (wheat, maize, rice, sorghum, millet, sweet potato, and legumes) because they dominate diets worldwide, especially among groups suffering from micronutrient deficiencies. Breeders often cross nutritious varieties (e.g., high in vitamin A, iron, or zinc) with high-yielding varieties.

1cv. Regional

Some seeds and plants are adapted to thrive in the soils, ecosystems, and climates where they originated. These relationships affect pest resistance, nutritional qualities including micronutrients and phytonutrients, flavors of foods, symbiotic ecological relationships with regional biodiversity, and resiliency in hot, cold, dry, or wet weather. For example, regional seeds and plant roots are often adapted to locally prevalent soil bacteria and fungi, or to weather conditions such as springtime rains followed by dry summer heat before moisture comes again (see **1e**). This results in different outcomes if seeds adapted to one condition are grown elsewhere, or if generic commercial seeds are grown in different regional conditions. Interestingly and relevant economically, these regional factors often correlate with regional food flavors and traditions as well.

1d. Seed management

In addition to seed genetics selected by the farmer, how seeds are produced and managed also affects product quality and other economic connections to farming practices.

1di. Organic seeds (as distinct from organically grown crops)

Some plants are grown to produce seeds themselves, rather than to produce food crops. Seeds produced by organically grown plants are better adapted in some ways to grow in natural or organic conditions than seeds produced by plants treated with pesticides and fertilizers. This frequently includes stronger natural resistance to pests and pathogens, which also correlates with phytonutrient production, as many phytonutrients are produced in response to stresses in the environment. On the other hand, pesticide regulations are less stringent for plants grown to produce seeds than for plants grown to produce food crops, presumably because these seeds are not intended for human consumption. Furthermore, because plants grown to produce seeds usually remain in the ground longer than food crops, farmers often need to manage pests and diseases for longer periods of time, so the pest control methods they select (chemical, organic, environmental or otherwise) also alter seed characteristics accordingly. More information about pesticides is summarized in the sections below about soil health (**2o**), ecosystems (**3e**), and human health (**6a**).

1dii. Microbial seed treatment before planting

Seeds contain their own microbes that help them grow when planted, including tapping nutrients and resisting diseases. Microbes in some seeds are being lost due to the domestication of crops and seed storage in dry environments. This also affects soil health (see **2q**) and plant growth (see **4f**) through seed-and-microbial relationships. Seeds can be soaked — also called bioprimed or inoculated — in specialized compost or other liquids containing species- or regionally-beneficial microorganisms to prepare them, soils, and plants for optimum vitality.

1e. Congruence with regional weather/pest/ecosystem conditions

As described in other parts of section (**1**) above, and relevant to several economic value propositions and market benefits, some varieties adapted to work synergistically with their local ecosystem: weather, soil type, and other plants, animals, and insects in the area. This often correlates with food flavors, social and cultural traditions and values, and nutrition as well.

2. Soil health

The USDA defines soil health as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans. Five USDA principles of maintaining soil health include: (1) maximize presence of living roots, (2) minimize soil disturbance, (3) maximize soil cover, (4) maximize biodiversity, and (5) livestock integration in some cases. Important components of soil health that correspond with many social and economic benefits include organic matter, carbon content, microbial abundance and diversity, water infiltration and retention, and aggregate stability. These, in turn, affect things like groundwater and aquifer recharge, nutrition and health (such as the human nutrient ergothioneine which is gaining attention for its antioxidant properties and is produced exclusively by fungi or microbes in soils and ecosystems), and other economic outcomes. The following farm practices affect soils directly.

2a. Cover crops
2b. No/low till
2c. Crop rotation
2d. Intercropping/polyculture
2e. Nutrient-fixing plants/trees
2f. Perennial planting
2g. Agroforestry
2h. % greenness during year
2i. Rotational grazing
2j. Antibiotics
2k. Synthetic fertilizers
2l. Bioactive composting
2m. Biochar
2n. Other soil amendments
2o. Pesticides
2p. Soil & air pollutants (PFAS, heavy metals, etc.)
2q. Microbial seed treatment before planting

2a. Cover crops

Cover crops are grown specifically to prevent erosion and improve soil health. They are grown in between cash crop harvests, although some farmers look for cover crops that can also be sold or generate market value in other ways. Examples of species used as cover crops include rye, cowpeas, buckwheat, radishes, and others. By covering the ground with this vegetation and maintaining living roots, but terminating it before it goes to seed, cover crops provide several benefits: they help stabilize the soil; protect fallow ground from erosion, heavy rainfall, and excess heat; they feed the life in the soil, continuing to photosynthesize sunlight and produce root exudates, sugars, and other sources of soil energy and nutrients that feed and sustain different types of underground microbes; they sequester carbon from the atmosphere and some fix nitrogen as well; they help maintain soil organic matter; and they help improve water absorption and prevent the leaching of nutrients out of soils through runoff and erosion. By maintaining living fields and plant diversity, cover crops may also help foster the additional benefits of above-ground biodiversity on and around a farm site.

2b. No till / low till

Some farmers till the soil — mechanically mix and turn it with a plow or other instrument — to loosen and aerate the topsoil to facilitate planting, destroy weeds, and/or incorporate crop residues into the soil. However, bare, unanchored, and disaggregated soil left exposed by tillage is also susceptible to water and wind erosion and runoff, and aggressive tillage is known to kill larger organisms such as earthworms and slice through beneficial underground fungal networks. Intensive tillage can also cause soil carbon loss and greenhouse gas emissions because it triggers more decomposition of organic matter. Organic no-till farms use hand tools or a roller crimper or mower which terminates the cover crop and seeds and drops the mulch, while conventional no-till farms can also use herbicides to kill cover crops. Tillage can also create a compaction layer deeper down, which limits some soil life and water's ability to infiltrate.

2c. Crop rotation

Crop rotation is the practice of growing different types of crops in the same location across a sequence of growing seasons. For example, alternating corn and soybean crops in the same field. More complex rotations may involve three or more crops in a five- to ten-year cycle. Crop rotation has been shown to be effective in controlling insects, weeds, diseases, and parasites. It also dramatically alters the composition of healthy mycorrhizal fungi communities, with greater fungal richness and diversity in rotated fields than in fields always used for the same crop. Diverse crop rotations have also shown improved overall soil fertility in fields, decreasing the need for fertilizer. The innovation technique of wetlands rotation through a property reflects this principle also, with fallow periods of three years or more absorbing fertilizer runoff from the farm and supporting native plant and soil regeneration before the plot is converted back into field for planting crops, with the wetland portion being migrated to an adjacent section. See (**2k**) for more information on this technique.

2d. Intercropping/polyculture

Intercropping/polyculture is the cultivation of two or more crops near each other. This is often done by planting one crop in-between the rows of another (strip cropping) or seeding a second crop into an established or already-growing crop (relay cropping). It can also include perennial polycultures, agroforestry, and agroecology which aim to mimic natural ecosystems. Companion planting is specifically designed around symbiotic relationships between particular plant species. Polycultures can benefit from spatial, seasonal, and nutritional complementarity among species. These growing methods can improve utilization of essential resources such as water, sunlight, and nutrients because different species have different resource requirements. Importantly, plant diversity of this type supports microbial diversity in the soil. However, mechanization for farm efficiency is also more difficult when different crops have different requirements or days to maturity. See also (**3a**) about the ecosystem benefits of plant diversity and (**4c**) about how intercropping/polyculture can benefit the plants directly.

2e. Nutrient-fixing plants/trees

Nitrogen-fixing plants and trees extract atmospheric nitrogen and convert, or fix it, into plant-available nitrates, nitrites, or ammonia in the soil. This reduces the need for chemical or other organic nitrogen fertilizers. Common nitrogen-fixing plants include vetch, alfalfa, peas, and legumes such as beans. Nitrogen-fixing plants are often used in crop rotations, in intercropping, and as cover crops. Many traditional and indigenous farming practices incorporate nitrogen-fixing plants such as beans to provide soil fertility alongside companion plants such as corn that provides structure for the beans to climb, or squash that helps shade the soil from excessive heat during hot summer days. Evidence shows that nitrogen-fixing relationships between plants and microbes is also inhibited in some circumstances by application of synthetic pesticides intended for other purposes.

2f. Perennial planting

Perennial plants regrow every year, whereas annual plants live for only one growing season. Examples of perennials include many fruit and nut trees, and grains such as kernza and some other historical varieties. Examples of annuals include corn, soybeans, wheat, beets, and the majority of vegetables. Annuals require the yearly clearing of vegetation and soil preparation for new planting in the following season, causing soil erosion and other forms of degradation (see no/low till in section **2b**). Perennials have roots that extend much deeper than annuals, often tapping otherwise out-of-reach nutrients deep in the soil, helping reduce nutrient leaching, and bringing nutrients to the surface in ways which are then used also by the wider ecosystem. Perennials maintain continuous living roots underground, protect the soil from erosion, build organic matter, provide habitat for microbes, sequester carbon, and support water infiltration.

2g. Agroforestry

Trees or shrubs integrated into farmland or pastures have expansive and sometimes deep root systems that reduce erosion; hold carbon and water; channel energy and nutrients into the deeper soils through photosynthesis; draw nutrients to the surface from deeper in the earth in many cases; and harbor microorganisms that are capable of supporting other soils in the area and repopulating soils after natural disasters or other damage. They can help keep moisture in the local ecosystem, add organic matter (including nitrogen in some cases through leguminous trees that fix nitrogen from the atmosphere), provide shade from excessive heat and heavy rainfall, and support water infiltration. Also see the wider ecosystem benefits of trees in (**3c**).

2h. % greenness during year

In general, when a landscape is green because plants are growing (and thus photosynthesizing), root exudates are being released into the soil. This is an indicator of soil nutrients being delivered and maintained through living roots. "Greenness" is also indicative of nitrogen in the environment through its role in the chlorophyll molecule that gives plants their green color. "% greenness" is therefore sometimes considered as a static indicator across the landscape at a point in time, or as a dynamic indicator across a time period. Also see the information about living ground cover in the sections above on cover crops (**2a**) and no/low till (**2b**).

2i. Rotational grazing

This is the practice of containing and moving animals throughout different portions of a pasture over time. Depending on local ecosystem and soil conditions, this process stimulates and supports life in the soil. It speeds the breakdown of plant material; tramples organic litter into the soil; breaks hard soil surfaces; naturally fertilizes and waters the land with manure, urine, and microbes; and stimulates plants to release root exudates that further support soil biology. By managing the density and movement of herds of grazing animals, increases may result in soil organic matter, carbon sequestration, below and above ground biodiversity, improved soil water-holding capacity, improved soil structure, greater rooting depth, increased plant cover above ground, and reduced runoff of organic pollution into waterways. See also (**3i**) on animal integration benefits to the greater ecosystem, (**4e**) for a comparison to CAFO practices for raising livestock (*concentrated animal feeding operations*), and (**4g**) regarding nutritional implications of different livestock diets.

2j. Antibiotics

Antibiotics (drugs frequently used to treat bacterial infections in people and animals) are often mixed into the feed given to animals raised in confined and crowded spaces to treat diseases or as preventative measures. If a single animal in a herd or flock is diagnosed with an illness, often the entire herd will be administered antibiotics. Low concentrations (called sub-therapeutic doses) are also often given to healthy animals to increase weight gain. Antibiotics are used more heavily with livestock than with people. When used as fertilizer or if contaminating waterways, manure from these animals can kill or alter the composition of soil bacteria and fungi. See (**4i**) for more on antibiotic usage with livestock and (**6d**) for their effects on human health.

2k. Synthetic fertilizers

Fertilizers are added to promote plant growth. Synthetic fertilizers are those manufactured with chemical or other inputs, in contrast to organic or natural fertilizers such as those made from wood ash or fish oils. The primary synthetic fertilizer inputs are the plant macronutrients nitrogen, phosphorus, and potassium (NPK).

In addition to macronutrients, micronutrient fertilization can include calcium, magnesium, sulfur, iron, zinc, manganese, copper, and more. Micronutrient fertilizers can be applied in several ways: in the form of salts, chelates, or mixtures with macronutrient fertilizers; as foliar spray; or via seed coating or seed priming (see **1dii**). This can be useful in soils which are naturally low in certain micronutrients, although successful delivery of less-soluble micronutrients like iron and zinc depends in part on microbial partnerships between the soils and plant roots, which are affected in other ways by fertilizers as summarized below.

Despite their value improving plant growth and yield in many situations, synthetic fertilizers can also have unintended consequences. Use of excess fertilizers over time can result in soil acidification, which limits natural nutrient bioavailability, and can lead to the accumulation of potentially toxic elements like cadmium, fluoride, radioactive elements, lead, arsenic, chromium, and nickel. Under heavy fertilization plants can become weakened, increasing the need for pesticides that can then cause other problems for soils (see **2o**), ecosystems (**3e**), and human health (**6a**). Some fertilizers disrupt soil biology directly by harming beneficial fungi, and indirectly by reducing symbiosis between plant roots and soil microbes, as plants no longer need the microbes to access nutrients, so the microbes that needed the plant roots for their own nutrients die off. This reduces fungal abundance and diversity in soil systems, with other agronomic and potential economic consequences. In fact, some plants and seeds that have been modified by breeding or GMO to work specifically with synthetic fertilizers have permanently lost their ability to work symbiotically with soil microbes in these ways, affecting this type of link between soils and nutrition. These factors can make the plant types and farms dependent on fertilizer inputs and related economics each year, and can affect natural micronutrient and phytonutrient availability and nutritional resiliency and security over time.

Beyond these effects on plants and soils, fertilizer not taken up by crops are also known to pollute waterways and water supplies through surface runoff or leaching, which is a major contributor to eutrophication — harmful oxygen deprivation, algal blooms, ocean acidification, and resulting dead zones. (Some creative economic systems such as rotating artificial wetlands that help restore native plants and wildlife, such as Lakeside Farms in Oregon, do successfully intercept these fertilizer flows before they reach the waterways). Energy intensive production and transportation of chemical fertilizers from fossil fuel sources is also attributed with significant agricultural sector impact on greenhouse gas emission.

2l. Bioactive composting

Compost can deliver beneficial microbes which spread in the soil. When prepared at large or small scale, an intentional mixture of organic matter, moisture, oxygen flow, and temperature produces a rich mix of soil amendments. For example, the *Johnson-Su bioreactor* is a system constructed at a farm site where microbes and fungi breed in a mix of manure and farm and yard waste that is fed aeration and water through a simple perforated pipe. Microbe- and nutrient-rich liquids can also be generated from finished bioactive compost and added to the soil or applied to the leaves as a foliar spray (see also **4a**). Bioactive compost can supplement or regenerate soil biology.

2m. Biochar

Biochar is a tiny granular form of carbon that can be mixed in soils or compost to add structure and granularity and help retain nutrients, microbes, and water. It is produced by slowly burning organic plant material (wood, cornstalks, peanut shells, etc.) in a low-oxygen environment (pyrolysis), leaving highly porous small granules of charcoal, rather than fine ash that would be produced if the materials were burnt fast at high heat. Biochar additions to soil and compost have been shown to increase plant nutrient availability, enhance water-holding capacity, increase soil cation exchange capacity, provide habitat for microorganisms, and increase soil pH. However, biochar produced with contaminated materials or fossil fuels can also hold concentrations of toxins and heavy metals that negatively impact soil and crop health.

2n. Other soil amendments

Other types of soil additives affecting plants, the surrounding ecosystem, and nutrition include non-synthetic fertilizers that add nutrients to the soil (e.g., kelp, fish meal, bone meal, rock powder/dust, vermicompost), and other biostimulants that help plants achieve maximum yield or growth by reducing stress or improving plant nutrition efficiency (e.g., humic and fulvic acids, amino acids, seaweed extracts, chitin, and microbial or fungal inoculants).

2o. Pesticides

Pesticides (including insecticides, fungicides, and herbicides) kill or prevent pests, certain fungi, molds, bacteria, viruses, and undesirable vegetation (weeds) that can damage crops. Depending on the pesticide type, half-life, concentration, and proximity to risk factors like water supplies or people's work sites or homes, pesticides can also cause harm. Some break down and dissipate quickly, while others significantly disrupt or destroy soil biology, killing microbes, reducing the abundance and diversity of healthy mycorrhizal fungi, and inhibiting hyphal growth and root colonization. Some are also toxic to natural biocontrol agents that help regulate other factors in the soil, leading to increased fungal pathogens. Evidence suggests that some pesticide applications also inhibit nitrogen-fixing relationships between leguminous plants and soil microbes (see **2e**). Some also leach through soils into groundwater. See also (**3e**) for pesticides' effects on the greater ecosystem and (**6a**) for pesticides' effects on human health.

2p. Soil & air pollutants (PFAS, heavy metals, etc.)

Soils can contain naturally occurring heavy metals, such as arsenic, copper, cadmium, chromium, and others. In some cases, heavy metals from human activity or from natural conditions can increase concentrations to dangerous levels, often referred to in government standards as *Maximum Residue Levels.* Heavy metals of concern in soils because of potential toxic concentrations and long-term persistence include arsenic, cadmium, lead, chromium, mercury, copper, zinc, and nickel. Soil is also a significant long-term reservoir of PFAS (*per- and polyfluoroalkyl substances*), a group of extremely durable man-made chemicals that have been used in industrial and consumer products for over 60 years, such as nonstick cookware, water resistant fabrics like tents and jackets, firefighting foams, and many more. PFAS can migrate into the soil, water, and air during production and use of these products, and because they do not break down, they remain in the environment. In addition to sometimes being toxic to people and animals, these pollutants can suppress microbial processes in the soil. See (**6e**) for more about these pollutants' effects on human health.

2q. Microbial seed treatment before planting

As summarized in (**1dii**) above, soaking or biopriming seeds in microbial-rich liquids or compost before planting can also affect soil health, because the microorganisms in the seeds then serve as a soil inoculum that introduces new microbial life in the soil. Microbial seed treatment can also impact the plant itself as summarized in (**4f**). It is important to note that, as opposed to microbial seed treatments, seeds can instead be treated with neonicotinoids or antifungals. While this protects the seed in the short term, it may also have effects on the soil microbes.

3. Ecosystem interdependence around the farm

Diversity and natural habitat in the ecosystem around a farm support aspects of nutrient cycling, soil health and fertility, pest control, pollination, local water cycles, nutrition, farm resiliency after weather disruptions, pollution reduction, and farmworker health and productivity. The health of the whole farm site ecosystem is increasingly seen as a critical property of sustainable food and natural resource systems. As the number of species increases, so do interdependencies and symbiosis among them, and the more stable and resilient the entire system tends to become. Below are practices and indicators that affect and are affected by interdependencies and biological diversity around the farm.

3a. Plant diversity
3b. % greenness during year
3c. Agroforestry
3d. Conserved natural habitat
3e. Pesticides
3f. Integrated pest management (IPM) & push-pull
3g. Habitat for pollinator health
3h. Perimeter plantings
3i. Animal integration

3a. Plant diversity

Plant diversity counts the number of crop or non-crop species. In general, a region with many plant species is more likely to contain higher functional diversity — plant groups with distinct roles in the ecological community. For example, legumes are able to fix nitrogen; perennials reduce erosion and runoff, significantly contribute to the formation of soil organic matter, and improve water infiltration and retention; certain plants attract beneficial predators which keep pests at bay (see **3e** and **3f** regarding ecosystem factors in pest management); other species provide habitat and food for pollinators. These all support each other. Each species also produces unique root exudates that attract and support different microbes in the soil, which improves soil health and all the consequent benefits in nutrients for plants and nutrition for people (also see **2d** regarding polyculture impact on soils). Plant monocultures, on the other hand, lack these attributes and are more dependent on synthetic fertilizers and pesticides for success.

3b. % greenness during the year

As summarized in (**2h**), % greenness of a site at a point in time or across time is sometimes seen as an indicator of life on the landscape that affects soil nutrients, nitrogen retention, carbon sequestration, erosion protection, and water infiltration. In this way, % greenness across time can, in certain conditions, reflect symbiosis between different elements in the surrounding ecosystem.

3c. Agroforestry

Multiple benefits can result from trees or shrubs integrated into farmland. In addition to soil health, nutrient, and water benefits described in (**2g**), agroforestry provides habitat in the wider ecosystem for other plant, fungal, insect, and animal species — biodiversity in various forms. Recognized forms of agroforestry include alley cropping (planting trees or shrubs to create rows for growing crops), forest farming (growing crops under tree canopies), silvopasture (integration of trees and livestock grazing), riparian buffers (areas of trees or shrubs along waterways to filter farm runoff and prevent erosion), and windbreaks (protects crops and prevents erosion).

3d. Conserved natural habitat

Setting aside natural habitat on or around a farm site helps provide the full range of benefits listed above: nutrient cycling both above and below ground; soil health and fertility through support for microbial life, woody biomass, and ongoing photosynthesis; natural pest control; pollination; local water cycles; nutrition; farm and landscape resiliency after weather disruptions; pollution reduction; carbon sequestration; and farmworker health and productivity. Farm site examples include hedgerows, wildflower planting, insectaries, prairie strips, buffer zones and adjacent conservation areas managed for wildlife/biodiversity, carbon benefits, and wild food harvesting.

3e. Pesticides

As discussed in the soil health section (**2o**), synthetic pesticides bring both substantial benefits and risks. In terms of ecosystem interdependence around the farm, pesticides can harm or destroy beneficial non-target organisms including microbes, fungi, and insects such as pollinators and natural sources of pest control like ladybugs and lacewings. In doing so, they disrupt the systemic relationships between those organisms and other supports for farm productivity and resiliency. The timing of pesticide applications is a key factor in their wider environmental impact, including before vs. after the springtime breeding of insects and wildlife, and during times of day when beneficial insects including pollinators are more prevalent and likely to be affected. Emerging technologies rooted in ecosystem interdependencies, such as precision analysis of pollen collected by bees around a farm site, also help provide farmers and others with statistical data on both the plant diversity and the presence and risk assessment of any pesticides in the region, informing actions to support and improve ecosystem interdependence around the farm. Also see (**6a**) for pesticides' effects on human health.

3f. Integrated pest management (IPM) & **push-pull**

IPM focuses on long-term control of pest risks to crops, including insects and weeds, by strategically combining ecosystem functions, biodiversity strategies, and targeted use pesticides only when needed. Whether deployed as part of IPM or on its own, the push-pull method uses decoy plants that attract pests to areas where they are trapped or preyed upon by beneficial insects, or companion plants that deter and repel insects away from food crops, such as lining a vegetable field with garlic or other plants that the pests avoid.

Examples of non-toxic or less-toxic pest control include creating habitat for beneficial insects which prey on pests, eliminating invasive weed species by mowing the weeds before they go to seed, or planting non-harmful crops such as alfalfa that choke out invasives. IPM strategies often track action thresholds for specific pests — points at which more aggressive actions must be taken if natural methods are not working sufficiently. IPM strategies may also include identifying and monitoring specific pests (many organisms are harmless or even beneficial), and 'hot spot' spraying to target only the specific site of an aggressive pest infestation rather than spraying a whole field.

3g. Habitat for pollinator health

Two-thirds of fruits and seeds rely on pollinators like bees for sustained yield and quality. Establishing wild habitat for pollinators on farmlands helps provide the nesting sites, shelter, and food pollinators need to thrive. A diversity of plants is especially important for meeting the nutritional requirements of pollinators, and for supporting a diversity of wild pollinators, which some farmers say bolsters crop productivity across variable weather conditions. New techniques in precision analysis of pollen collected by the bees themselves across wide landscapes (i.e. over 30,000 sample-collecting bees per beehive every day) can provide specific data on farm characteristics including the details of pollinator-friendly habitat, including plant diversity statistics and trends, availability of amino acids needed by pollinators in their own diets, and habitat risk factors like presence or high concentrations of particular chemicals.

3h. Perimeter plantings

As noted in the discussion of IPM and push-pull pest management (**3f**), in some circumstance, varieties of plants that are especially attractive to insect pests can be planted around a field perimeter. Insects moving in from the edges of the field tend to concentrate in the perimeter crop and are less likely to reach and damage the main crops in the center of the field.

3i. Animal integration

As crop and animal production has specialized, historically common integration of the two has declined substantially in society. Where animals and crops traditionally created closed nutrient and water loops with each other on the same landscapes, they have become separated in many places today. In addition to the soil health benefits of animals as discussed in (**2i**), other benefits can include on-farm sources of microbially-rich inputs for compost, natural weed management, and reduced animal feed costs. Livestock are used by no-till farms to terminate and integrate cover crops. Examples of integrated crop-livestock systems show increased biodiversity; lower fertilizer requirements; reduced economic risk through diversification; increased health and well-being of the farm animals; and increased farmworker health, happiness, and productivity.

4. Plant or animal management practices

Farmers can manage the plant or animal itself — aside from managing the seed and breed selection, soil, surrounding ecosystem, and use of potentially harmful chemicals — in ways that affect food quality and other economic results.

4a. Foliar spray
4b. Sunlight (canopy; in/outdoors)
4c. Intercropping/polyculture
4d. Pollination via animal, self-, other
4e. Rotational grazing
4f. Microbial seed treatment before planting
4g. Feed type (grain, grass, diverse natural pasture)
4h. Exogenous hormones

4i. Exogenous antibiotics

4a. Foliar spray

Spraying plants directly with carefully developed liquids that deliver beneficial biology or micronutrients, through the plant's leaf pores and stomata, can support plant health and crop results. Foliar sprays, which are often organic and customized by farmers with nutrients particular to the plant variety, can increase general plant growth, as well as specific nutrient content such as iodine, iron, and zinc in edible portions of crops. They can also reduce the volume of water needed to grow crops. For example, with the well-documented Korean Natural Farming (KNF) approach, farmers cultivate and apply microbes adapted to the specific local environment. With foliar spray, nutrients are absorbed by the plant more quickly, allowing farmers to address plant nutrition problems faster when identified. Foliar spray can also reduce runoff and leaching compared to soil-based methods of fertilization.

4b. Sunlight (in/outdoors; canopy)

Managing the sunlight a plant receives – through pruning, canopy management for shade, and outdoor vs. indoor growing – affects its overall growth and certain nutritional qualities. Some plants thrive in low levels of sunlight, others require high levels. Flavonoids, an important type of phytonutrient for human health, are produced by plants in some cases as UV-protection, and sunlight has been shown to trigger production of anthocyanin (a type of flavonoid). Plant exposure to sunlight is also key to vitamin C content in some crops such as tomatoes, grapefruit, and kiwi.

More generally, all life above and below ground depends on plants' ability to convert sunlight into energy through photosynthesis. Photosynthesis through plants is the only way to bring new energy into the Earth's ecosystems. Energy for soils and ecosystems can be captured by increasing the density of vegetation on a unit of land, increasing the length of time during the year of vegetative growth on a site, increasing the rate at which the vegetation grows, or by expanding the leaf area of individual plants.

4c. Intercropping/polyculture

This is the practice of cultivating multiple crops near each other, in rows or plots, or in perennial polycultures, agroforestry, or agroecology which aims to mimic natural ecosystems. As discussed in (**2d**) regarding soil health, intercropping/polyculture can also help create self-sustainable pest management, natural soil fertility, localized habitat for beneficial insects, and other systemic benefits. Polycultures can benefit from spatial, seasonal, and nutritional complementarity among species. A popular example is the "three sisters," an Indigenous agriculture tradition in some areas, whereby corn, beans and squash support each other with individual strengths that allow the whole to flourish. The corn emerges first and provides a straight and stiff vertical support around which the bean vine can climb. The squash extends over the ground below the corn and beans, keeping in moisture, controlling weeds, and providing protection from predators with their prickly leaves and vines. The beans fix nitrogen from the air into the soil, providing natural fertilizer for the corn and squash.

4d. Pollination via animal, self, or other

Flowering plants rely on pollination to reproduce. Pollination can occur by animals/insects such as bees, butterflies, flies, and moths; through the wind; mechanically by humans; or via self-pollination of a plant by itself. Insect pollinators have been shown to increase food product yield and shelf-life, and to reduce the need for some pesticides and growth regulators, because of the stimulation and additional biological elements like beneficial regional fungi and amino acids that they bring to the plant. For example, insects have also been shown to improve the fatty acid composition of almonds because of how they stimulate the plant's pistil.

4e. Rotational grazing

This is the practice of containing and moving livestock throughout different portions of a pasture over time, rather than letting them free-range across the pasture wherever and whenever they want or keeping them in enclosed pens with concentrated feeding operations (often called CAFOs or *concentrated animal feeding operations).* Livestock production in the U.S. is dominated by CAFOs. In addition to rotational grazing's soil health and other farm resource benefits (see **2i**) and wider ecosystem interdependence benefits (see **3i**), proponents suggest that rotational grazing improves animal and farmworker wellbeing. See (**4g**) below for information on the relationship between rotational grazing, biodiversity, and nutritional qualities of meats and dairy.

4f. Microbial seed treatment before planting

As introduced under seed management in (**1dii**), inoculating seeds with microbes prior to planting has been shown to increase plant nutrient uptake; increase phytonutrient levels; increase tolerance to abiotic stress, including water scarcity, heavy metal toxicity, and salinity; increase biotic stress tolerance against disease; and increase plant growth promoting activity (e.g., root and shoot length).

4g. Feed type (grain, grass, diverse natural pasture)

Animals raised in feedlots or other confinement often eat a concentrated mix of corn and soybean seeds, or of *total mixed rations* (TMR), an engineered mixture of protein, carbohydrates, fats, minerals, and vitamins. Others are grassfed, and some are raised in even more biodiverse pastures where they can self-select among a range of living plants.

What animals eat affects variations in the fatty acid and phytonutrient profiles of the meat and dairy they produce. For example, metabolomic research published in late 2023 shows that pasture-raised animals have improved metabolic health compared to feedlot animals, evidenced by reduced cortisol and blood glucose levels. The resulting meat for human consumption from animals that graze on biodiverse pastures compared to those that consume processed feeds shows improved omega-3: omega-6 ratios, more micronutrients, and increased phytonutrient levels.

Additionally, the healthy fat *conjugated linoleic acid* (CLA) is found almost exclusively in ruminant meat and dairy, being produced by rumen-dwelling bacteria. A healthy rumen microbial ecosystem, including fiber for the microbes to eat, are important for CLA production.

It is believed that low-fiber, high-starch feedlot rations in feedlot and other concentrated feeding systems can disrupt rumen microbial ecologies, causing the rumen pH to become overly acidic, which can lead to various acute and chronic conditions. Antibiotics (see **4i**) are often administered in response, which can further increase microbial dysbiosis or imbalance, as well as mitochondrial dysfunction and increased oxidative stress, affecting meat and dairy quality in the ways described above.

4h. Exogenous hormones

Conventionally raised livestock are often given hormones, including estrogen, testosterone, and progesterone, to increase their growth and milk production. Some analyses suggest that using hormones to increase production in this way can also reduce the amount of cropland needed by the meat and dairy industries, and can consequently reduce greenhouse gas emissions as well. However, some concern exists about their impact on other aspects of milk production, animal health, and human health (see **6c**). For example, *Recombinant Bovine Growth Hormone* (rBGH) has also been shown in cows to increase the incidence of mastitis, an infection of the udder, which consequently results in increased use of antibiotics in those dairy cows (see **4i**). While the U.S. Food and Drug Administration has approved the use of farm animal hormones like this, the European Union banned the use of growth hormones in livestock in the 1980s, and the ban was later extended to include the import of hormone-treated meat.

4i. Exogenous antibiotics

Antibiotics, as discussed regarding impact on soil health in (**2j**), are often administered to livestock to prevent or treat infections, as well as to promote growth. However, many countries have restricted the use of antibiotics in livestock in an attempt to preserve the effectiveness of antibiotics for fighting diseases in people (see **6d**). The European Union banned the use of antimicrobial growth promoters in 2006. In 2023, the U.S. Food and Drug Administration transitioned to prescription-only the availability of antibiotics that are medically important for humans but were previously available over the counter.

5. Post-harvest crop management

What a farmer does with a crop after it is harvested but before it is sold or shipped away can affect the food's nutritional qualities and the other potential economic values that result from on-farm practices.

5a. Location/proximity/transport
5b. Date/freshness
5c. On-site food processing
5d. Storage conditions (temperature, growth regulators)
5e. Maturity of crop at time of harvest

5a. Location/proximity/transport

Some farmers sell in local markets, while others sell regionally, nationally, or internationally. The distance and type of transportation affects freshness and flavors (**5b**), storage (**5d**), and use of some chemicals. For example, when shipping fruits over large distances, farmers often use cold storage and growth regulators so that fruit can be picked while it is still green (see **5e**) and then ripened using ripening compounds or other procedures upon arrival at its destination. Local foods also connect with community and cultural values and traditions, and with local food system resiliency in cases when longer distance supply chains are disrupted. Transportation distance and cold storage also affect greenhouse gas emissions during shipping.

5b. Date/freshness

How soon a crop is available for consumption after harvest is affected by location/proximity (**5a**) and length of storage (**5d**). Some nutrients decline relative to the time since a crop was harvested, while others are more stable. Freshness also impacts flavor.

The health and medical fields generally recommend fresh foods for several reasons: they add nutritional diversity to the diets of people that rely largely on processed foods; they include nutrients that don't store well so are not present in less fresh or processed foods; they tend to contain a full package of essential nutrients (vitamins, minerals, phytonutrients, fiber, etc.), rather than just nutritional elements that have not been refined out or have been added in during processing; and they don't include the artificial ingredients of many processed foods that can cause inflammation and oxidative stress in the human body, contributing to discomfort and chronic disease. Fresh foods are also important to the flavors, aromas, preparation, and seasonal traditions in many cultures.

As noted above, while most fresh foods offer these benefits, the freshest is not always the most nutritious. While many nutrients decline from time of harvest, this varies by the specific crop and nutrient; some may actually increase for some time in nutritional qualities like bioavailability. Some foods deteriorate quickly (imagine a fresh peach at room temperature), while others are more stable and can last longer (like a carrot). Studies show that apples with long shelf life hold certain nutrients, but tend to lose others, to the degree that many "well-aged" apples available after long periods of storage tend to have very high sugar content and fewer of their original diversity of nutrients.

5c. On-site food processing

Cooking, canning, grain milling technique (roller or stone milling), flash freezing, freeze drying, dehydrating, or combining with other food additives for nutritional or preservation reasons affects various nutritional qualities. Some preserve nutrients in various ways, while others deplete them. These can include some micronutrients, phytonutrients, whether fiber remains part of the final food source, particle size and protein content of the food (such as whether grain milling separates endosperm from bran and germ), traditional flavors, baking qualities of the product, etc. Farms that process foods on-site before sale and distribution may, therefore, be affecting nutritional qualities in ways other than through the farm's growing practices.

5d. Storage conditions

Length of storage time, temperature, and humidity can affect nutritional quality. Cold storage and modified atmosphere packaging are used to extend the shelf life of perishable foods. Grains are sometimes stored for months or years on a farm site. The effects on fruits and vegetables vary considerably depending on the crop and the compound. Cold storage systems also consume energy, thereby affecting on-farm greenhouse gas emissions depending on their fuel source, and may involve hormones and chemicals called growth regulators.

5e. Crop maturity at time of harvest

Harvest variables include the maturity of the crop at time of harvest (e.g. was it harvested when ripe for immediate use or marketing, earlier in order to facilitate storage and transport, or at another point to optimize certain flavor qualities or food processing requirements) and the time of the season a crop was harvested (e.g., early, mid, or late-season). This can affect some nutritional qualities, such as how much vitamin C developed in tomatoes before they were picked. These factors correlate with various nutritional qualities.

6. Compounds that can be harmful to humans

Chemical compounds and other elements are sometimes used by farmers to help with pest management, crop growth, and crop storage. Some of these can also be toxic or harmful to humans in certain situations. Other potentially harmful compounds and elements may be present at a farm, including PFAS and heavy metals, because of past land uses, leaching through soils or water sources from other locations, or drift through the air from elsewhere. In unfortunate circumstances, the multifaceted effects of these compounds may also affect local residents, farm workers, or food consumers.

The sections noted below introduce how these compounds are used and may interact with other on-farm impacts including soil health, ecosystem conditions including other plants and animals, pollinators, water, cultural values and community priorities, pollution management efforts, and land values. They're listed in this note because they reflect multi-faceted economic impacts and opportunities of the farm site.

6a. Pesticides
6b. Chemical fertilizers
6c. Exogenous hormones
6d. Exogenous antibiotics
6e. Heavy metals and PFAS

6a. Pesticides

Typical uses, benefits, and conditions determining environmental and health risks of pesticides are discussed in sections (**2o**), (**3e**), and (**3f**). Factors affecting human health risks of pesticides include chemical formulation, concentration, overlapping applications with other pesticides, type of application (i.e. direct to soil, direct to plant, or airborne), proximity to sources of food and drinking water, and proximity to peoples 'homes or workspaces. Regulatory limits on pesticides are often guided by how fast they dissipate, whether they are water soluble, and the level at which scientific research shows any impact on human health. Some analysts suggest that regulatory limits on pesticides account only for acute but not chronic effects of low-level exposure over the long term, do not account for the potential synergistic effects of multiple pesticides, and do not account for the effects from one generation to the next through epigenetics.

6b. Chemical fertilizers

Various impacts beyond supporting plant growth and crop yield are discussed in section (**2k**), such as accumulation of potentially toxic elements and destructive runoff into waterways.

6c. Exogenous hormones

See (**4h**) and (**4i**) for discussion about how hormone use in cattle to improve meat or dairy yield can also affect greenhouse gas emissions and use of antibiotics as well.

6d. Exogenous antibiotics

In addition to affecting animal health (**4i**) and soil health (**2j**), some research suggests that excess use and misuse of antibiotics with farm animals may be the largest source of antibiotic-resistant bacteria and a leading cause of antibiotic-resistant infections in people. This occurs when microbes evolve to protect themselves from antibiotic drugs and are transmitted to humans through direct animal contact, exposure to manure, contact with raw or undercooked meat, and in other ways. Antibiotics can also disrupt the human gut microbiome.

6e. Heavy metals and PFAS

In addition to the effects of these compounds in soils, as discussed in (**2p**), many of them can be quite harmful to humans depending on form and concentration. For example, lead, cadmium, arsenic, and others have parts-per-million regulatory limits guiding their permissible levels in foods, and some dairy farms have stopped selling milk because of PFAS contamination connected to historical spreading of processed municipal waste sludge on their fields, which was thought at the time just to increase soil nutrients while providing an economical and smart channel for waste disposal. If present, these PFAS compounds can sometimes be taken up by plants from the soil, can leach into groundwater, and can be inhaled by people or animals. Plant pollen can also be coated with such compounds when bound to dust in the air.

III. REFERENCE LIST

This diagram serves as a science-based assessment of economic opportunities for farmers, other business and social entrepreneurs, community leaders, policymakers, investors, and others. The intent is not to analyze the science itself, but to reflect what is currently known in illustrating interrelationships and linkages to the economics.

The reference materials listed below provide some background information and a starting point for further research on each of the framework's topics. These references are organized according to the topics in the diagram.

General Background Resources

The library of podcasts, webinars, and articles of John Kempf–an expert in the field of biological and regenerative farming who shares information about the capabilities of regenerative agriculture systems, and the science to put these management practices together.

Rodale Institute's long-term trials and research articles–Rodale's mission is to grow the regenerative organic agriculture movement through rigorous research designed to help uncover the most effective, efficient, and regenerative farming practices; farmer training; and education.

Acres U.S.A. monthly magazine–a great source for real-world, applicable information about regenerative/ecological agriculture for farmers, ranchers, growers, and those who work with them.

Dr. Elaine Ingham's Soil Food Web School YouTube video series–Elaine is a widely recognized soil biologist who is passionate about empowering ordinary people to bring the soils in their community back to life.

Montgomery, D. R. & Biklé, A. *What Your Food Ate*. (Norton & Company, Inc., 2022).

Gliessman, S. R. *Agroecology: The Ecology of Sustainable Food Systems, Third Edition*. (CRC Press, 2014).

Bargués-Tobella, A., Winowiecki, L. A., Sheil, D. & Vågen, T-G. Determinants of soil field-saturated hydraulic conductivity across sub-saharan Africa: Texture and beyond. *Water Resources Research* 60, e2023WR035510 (2024).

Varietal & Breed

(Relates to: Initial seed/plant/animal selection)

Zamaratskaia, G., Gerhardt, K. & Wendin, K. Biochemical characteristics and potential applications of ancient cereals – An underexploited opportunity for sustainable production and consumption. *Trends in Food Science & Technology* **107**, 114-123 (2021).

Kurilich, A. C. *et al*. Carotene, tocopherol and ascorbate contents in subspecies of *brassica oleracea. Journal of Agricultural and Food Chemistry* **47**, 1576-1581 (1999).

Laurora, A., Bingham, J. P., Poojary, M. M., Wall, M. M. & Ho, K. K. H. Y. Carotenoid composition and bioaccessibility of papaya cultivars from Hawaii. *Journal of Food Composition and Analysis* **101**, 103984 (2021).

Robinson, J. *Eating on the Wild Side*. (Little, Brown and Company, 2013).

Jianqin, S., Leiming, X., Lu, X., Yelland, G. W., Ni, J. & Clarke, A. J. Effects of milk containing only A2 beta casein versus milk containing both A2 and A2 beta casein proteins on gastrointestinal physiology, symptoms of discomfort, and cognitive behavior of people with self-reported intolerance to traditional cows' milk. *Nutrition Journal* **15**, 35 (2015).

Heritage, Hybrid, GMO, Biofortified, Regional & Organic Seeds
(Relates to: Initial seed/plant/animal selection)

Morris, C. E. & Sands, D. C. The breeder's dilemma—yield or nutrition? *Nature Biotechnology* **24**, 1078-1080 (2006).

Cobb, A. B. *et al*. The role of arbuscular mycorrhizal fungi in grain production and nutrition of sorghum genotypes: Enhancing sustainability through plant-microbial partnership. *Agriculture, Ecosystems and Environment* **233**, 432-440 (2016).

Elbon, A. & Whalen, J. K. Phosphorus supply to vegetable crops from arbuscular mycorrhizal fungi: A review. *Biological Agriculture & Horticulture* **31**, 73-90 (2014).

Jacoby, R., Peukert, M., Succurro, A., Koprivova, A. & Kopriva, S. The role of soil microorganisms in plant mineral nutrition–current knowledge and future directions. Frontiers in Plant Science **8**, 1617 (2017).

http://en.wikipedia.org/wiki/Genetically_modified_crops.

Bouis, H. E. & Saltzman, A. Improving nutrition through biofortification: A review of evidence from HarvestPlus, 2003 through 2016. *Global Food Security* **12**, 49-58 (2017).

Saltzman, A. *et al*. Biofortification: progress toward a more nourishing future. *Global Food Security* **2**, 9-17 (2013).

Brotak, E. Plant adaptations help them survive climate extremes. *Horticulture*. https://hortmag.com/smart-gardening/plant-adaptations (2023).

Zahedi, S. M., Karimi, M. & Venditti, A. Plants adapted to arid areas: Specialized metabolites. *Natural Product Research* **35**, 3314-3331 (2021).

Hubbard, K., Zystro, J. & Wood, L. State of Organic Seed. *Organic Seed Alliance*. http://stateoforganicseed.org/wp-content/uploads/2022/08/OSA-2022StateofOrganicSeed-06PRINT.pdf (2022).

Sawers, R. J., Gutjahr, C. & Paszkowski, U. Cereal mycorrhiza: an ancient symbiosis in modern agriculture. *Trends in Plant Science* **13**, 93-97 (2006).

Cobb, A. B. *et al*. Utilizing mycorrhizal responses to guide selective breeding for agricultural sustainability. *Plants, People, Planet*. **00**, 1-10 (2020).

Goldstein, W. Testing N efficient, high methionine corn hybrids with organic farmers. *Mandaamin Institute*. https://www.eorganic.info/sites/eorganic.info/files/u461/Mandaamin%20Final%20report%20SARE%20Project%20LNC17-389.pdf (2022).

Shahzad, R., Khan, A. L., Bilal, S., Asaf, S. & Lee, I.-J. What Is There in Seeds? Vertically Transmitted Endophytic Resources for Sustainable Improvement in Plant Growth. *Frontiers in Plant Science* **9**, 24 (2018).

White, J. F. *et al*. Review: Endophytic microbes and their potential applications in crop management. *Pest Management Science* **75**, 2558-2565 (20109).

Microbial Seed Treatment Before Planting
(Relates to: Initial seed/plant/animal selection; Soil health; Plant or animal management practices)

Chakraborti, S., Bera, K., Sadhukhan, S., & Dutta, P. Bio-priming of seeds: Plant stress management and its underlying cellular, biochemical and molecular mechanisms. *Plant Stress* **3**, 100052 (2022).

Devika, O. S. *et al*. Seed priming: A potential supplement in integrated resource management under fragile intensive ecosystems. *Frontiers in Sustainable Food Systems* **5**, 654001 (2021).

Mahmood, A., Turgay, O. C., Farooq, M. & Hayat, R. Seed biopriming with plant growth promoting rhizobacteria: A review. *FEMS Microbiology Ecology* **92**, 8 (2016).

Adhikary, S., Naskar, M. K. & Biswas, B. Seed priming—one small step for farmer, one giant leap for food security: II mechanism and manifestation. *Journal of Pharmacognosy and Phytochemistry* **10**, 409-412 (2021).

Cover Crops
(Relates to: Soil health)

Blanco-Canqui, H. & Ruis, S. J. Cover crop impacts on soil physical properties: A review. *Soil Science Society of America Journal* **84**, 1527-1576 (2020).

Thavarajah, D., Siva, N., Johnson, N., McGee, R. & Thavarajah, P. Effect of cover crops on the yield and nutrient concentration of organic kale (*Brassica oleracea* L. var. *acephala*). *Scientific Reports* **9**, 10374 (2019).

Saleem, M. *et al*. Cover crop diversity improves multiple soil properties via altering root architectural traits. *Rhizosphere* **16**, 100248 (2020).

Bowles, T. M., Jackson, L. E., Loeher, M. & Cavagnaro, T. R. Ecological intensification and arbuscular mycorrhizas: a meta-analysis of tillage and cover crops effects. *Journal of Applied Ecology* **54**, 1785-1793 (2016).

No/Low Till
(Relates to: Soil health)

Kabir, Z. Tillage or no-tillage: Impact on mycorrhizae. *Canadian Journal of Plant Science* **85**, 1 (2005).

Sengupta, A. & Dick, W. A. Bacterial community diversity in soil under two tillage practices as determined by pyrosequencing. *Microbial Ecology* **70**, 853-859 (2015).

Zuber, S. M. & Villamil, M. B. Meta-analysis approach to assess effect of tillage on microbial biomass and enzyme activities. *Soil Biology and Biochemistry* **97**, 176-187 (2016).

Beelman, R. B. *et al*. Soil disturbance impact on crop ergothioneine content connects soil and human health. *Agronomy* **11**, 2278 (2021).

Crop Rotation
(Relates to: Soil health)

McDaniel, M. D., Tiemann, L. K. & Grandy, A. S. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. *Ecological Applications* **24**, 560-570 (2014).

Jansa, J., Wiemken, A. & Frossard, E. The effects of agricultural practices on arbuscular mycorrhizal fungi. *Geological Society, London, Special Publications* **266**, 89-115 (2006).

Hendrix, J. W., Guo, B. Z. & An, Z. Q. Divergence of mycorrhizal fungal communities in crop production systems. *Plant and Soil* **170**, 131-140 (1995).

Walking Wetlands: Integrating Wetlands and Agriculture in the Upper Klamath Basin of California and Oregon. *U.S. Fish & Wildlife Service*. https://www.fws.gov/story/2021-11/walking-wetlands (2021).

Intercropping/polyculture, Nutrient-fixing Plants/Trees & Perennial Planting
(Relates to: Soil health; Ecosystem interdependence around the farm; Plant or animal management practices)

Duchene, O., Vian, J.-F. & Celette, F. Intercropping with legume for agroecological cropping systems: Complementarity and facilitation processes and the importance of soil microorganisms. A review. *Agriculture, Ecosystems & Environment* **240**, 148-161 (2017).

Brooker, R. W. *et al*. Improving intercropping: A synthesis of research in agronomy, plant physiology and ecology. *New Phytologist* **206**, 107-117 (2015).

Kaba, J. S. *et al*. Atmospheric nitrogen fixation by gliricidia trees (*Gliricidia sepium* (Jacq.) Kunth ex. Walp.) intercropped with cocoa (*Theobroma cacao* L.). *Plant and Soil* **435**, 323-336 (2019).

Iverson, A. L. *et al*. Review: Do polycultures promote win-wins or trade-offs in agricultural ecosystem services? A meta-analysis. *Journal of Applied Ecology* **51**, 1593-1602 (2014).

Crews, T. E., Carton, W. & Olsson, L. Is the future of agriculture perennial? Imperatives and opportunities to reinvent agriculture by shifting from annual monocultures to perennial polycultures. *Global Sustainability* **1**, 1-18 (2018).

Perennial Grain Crops: New Hardware for Agriculture. *The Land Institute*. https://landinstitute.org/our-work/perennial-crops/.

% Greenness During Year
(Relates to: Soil health; Ecosystem interdependence around the farm)

Gough, C. M. Terrestrial primary production: Field for life. *Nature Education Knowledge* **3**, 28 (2011).

Drinkwater, L. E. & Snapp, S. S. Advancing the science and practice of ecological nutrient management for smallholder farmers. *Frontiers in Sustainable Food Systems* **6**, 921216 (2022).

Schwartz, J. D. Soil as carbon storehouse: New weapon in climate fight? *Yale Environment 360*. http://e360.yale.edu/features/soil_as_carbon_storehouse_new_weapon_in_climate_fight (2014).

Plant Diversity
(Relates to: Ecosystem interdependence around the farm)

Tamburini, G. *et al*. Agricultural diversification promotes multiple ecosystem services without compromising yield. *Science Advances* **6**, 45 (2020).

Lin, B. B. Resilience in agriculture through crop diversification: Adaptive management for environmental change. *BioScience* **61**, 183-193 (2011).

Beillouin, D., Ben-Ari, T., Malézieux, E., Seufert, V. & Makowski, D. Positive but variable effects of crop diversification on biodiversity and ecosystem services. *Global Change Biology* **27**, 4697-4710 (2021).

Duffy, J. E., Godwin, C. M. & Cardinale, B. J. Biodiversity effects in the wild are common and as strong as key drivers of productivity. *Nature* **549**, 261-264 (2017).

Lundgren, J. G. & S. W. Fausti. Trading biodiversity for pest problems. *Science Advances* **1**, 6 (2015).

Tilman, D., Wedin, D. & Knops, J. Productivity and sustainability influenced by biodiversity in grassland ecosystems. *Nature* **379**, 718-20 (1996).

Isbell, F. *et al*. Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature* **526**, 574-77 (2015).

Conserved Natural Habitat
(Relates to: Ecosystem interdependence around the farm)

Fischer, J., Lindenmayer, D. B., & Manning, A. D. Biodiversity, ecosystem function, and resilience: ten guiding principles for commodity production landscapes. *Frontiers in Ecology and the Environment* **4**, 80-86 (2006).

Dainese, M. *et al*. A global synthesis reveals biodiversity-mediated benefits for crop production. *Science Advances* **5**, eaax0121 (2019).

Imhoff, D. Habitat Conservation: Habitat & Farmlands. *Defenders of Wildlife*. https://defenders.org/sites/default/files/publications/habitat_and_farmlands.pdf (2004).

Integrated Pest Management, Push-pull & Perimeter Plantings
(Relates to: Ecosystem interdependence around the farm)

Cai, Z. *et al*. Biological control of *Aphis spiraecola* in apples using an insectary plant that attracts and sustains predators. *Biological Control* **155**, 104532 (2021).

Tiwari, S., Sharma, S. & Wratten, S. D. Flowering alyssum (*Lobularia maritima*) promote arthropod diversity and biological control of *Myzus persicae*. *Journal of Asia-Pacific Entomology* **23**, 634-640 (2020).

Boucher, T. & Durgy, R. Demonstrating a perimeter trap crop approach to pest management on summer squash in New England. *The Journal of Extension* **42**, 5 (2004).

Shiva, V. *Agroecology & Regenerative Agriculture*. (Synergetic Press, 2022).

Pollination & Habitat for Pollinator Health
(Relates to: Plant or animal management practice; Ecosystem interdependence around the farm)

Arathi, H. S., Davidson, D. & Mason, L. Creating Pollinator Habitat. *Colorado State University Extension*. https://extension.colostate.edu/topic-areas/insects/creating-pollinator-habitat-5-616 (2018).

Bees and Other Pollinators. FAO's Global Action on Pollination Services for Sustainable Agriculture. *Food and Agriculture Organization of the United Nations*. http://www.fao.org/pollination/background/bees-and-other-pollinators/en/.

Morandin, L. A. & Kremen, C. Hedgerow restoration promotes pollinator populations and exports native bees to adjacent fields. *Ecological Applications* **23**, 829-839 (2013).

Adamson, N. L., Borders, B. & Cruz, J. K. Native Bee Conservation. Pollinator Habitat: Assessment Form and Guide. Farms and Agricultural Landscapes. *The Xerces Society for Invertebrate Conservation*. https://www.xerces.org/sites/default/files/2018-05/15-031_03_XercesSoc_HabitatAssessGuide_Pollinators_Farms%2BAg_web.pdf (2015).

Brittain, C., Kremen, C., Garber, A. & Klein, A. M. Pollination and plant resources change the nutritional quality of almonds for human health. *PLoS ONE* **9**, e90082 (2014).

Agroforestry

(Relates to: Soil health; Ecosystem interdependence around the farm)

Udawatta, R. P., Gantzer, C. J. & Jose, S. Agroforestry Practices and Soil Ecosystem Services. In: *Soil Health and Intensification of Agroecosystems* (eds. Al-Kaisi, M. M. & Lowery, B.) 305-333 (Elsevier, 2017).

Jose, S. Agroforestry for ecosystem services and environmental benefits: An overview. *Agroforestry Systems* **76**, 1-10 (2009).

Udawatta, R. P., Rankoth, L. M. & Jose, S. Agroforestry and biodiversity. *Sustainability* **11**, 2879 (2019).

Dollinger, J. & Jose, S. Agroforestry for soil health. *Agroforestry Systems* **92**, 213-219 (2018).

Rotational Grazing & Animal Integration

(Relates to: Soil health; Ecosystem interdependence around the farm; Plant or animal management practices)

Teague, R. & Kreuter, U. Managing grazing to restore soil health, ecosystem function, and ecosystem services. *Frontiers in Sustainable Food Systems* **4**, 534187 (2020).

Teague, W. R. *et al*. Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. *Agriculture, Ecosystems and Environment* **141**, 310-322 (2011).

Savory, A. *Holistic Management: A Commonsense Revolution to Restore our Environment*. (Island Press, 2016).

Teague, W. Forages and pastures symposium: cover crops in livestock production: whole-system approach: managing grazing to restore soil health and farm livelihoods. *Journal of Animal Science* **96**, 1519-1530 (2018).

Bansal, S., Chakraborty, P. & Kumar, S. Crop-livestock integration enhanced soil aggregate-associated carbon and nitrogen, and phospholipid fatty acid. *Scientific Reports* **12**, 2781 (2022).

de Faccio Carvalho, P. C. *et al*. Managing grazing animals to achieve nutrient cycling and soil improvement in no-till integrated systems. *Nutrient Cycling in Agroecosystems* **88**, 259-273 (2010).

Peterson, C. A., Deiss, L. & Gaudin, A. C. M. Commercial integrated crop-livestock systems achieve comparable crop yields to specialized production systems: A meta-analysis. *PLoS One* **15**, e0231840 (2020).

van Vliet, S. *et al*. Pasture-finishing of bison improves animal metabolic health and potential health-promoting compounds in meat. *Journal of Animal Science and Biotechnology* **14**, 1-18 (2023).

Pesticides

(Relates to: Soil health; Ecosystem interdependence around the farm; Compounds that can be harmful to humans)

Edlinger, A., Garland, G. & Banerjee, S. Agricultural management and pesticide use reduce the functioning of beneficial plant symbionts. *Nature Ecology & Evolution* **6**, 1145-1154 (2022).

Vázquez, M. B., Moreno, M. V., Amodeo, M. R. & Bianchinotti, M. V. Effects of glyphosate on soil fungal communities: A field study. *Revista Argentina de Microbiologia* **53**, 349-358 (2021).

Wang, X. *et al*. Fungicide azoxystrobin induced changes on the soil microbiome. *Applied Soil Ecology* **145**, 103343 (2020).

Fox, J. E., Gulledge, J., Engelhaupt, E., Burow, M. E. & McLachlan, J. A. Pesticides reduce symbiotic efficiency of nitrogen-fixing rhizobia and host plants. *Proceedings of the National Academy of Sciences* **104**, 10282-10287 (2007).

Kim, K.-H., Kabir, E. & Jahan, S. A. Exposure to pesticides and the associated human health effects. *Science of the Total Environment* **575**, 525-535 (2017).

Nicolopoulou-Stamati, P., Maipas, S., Kotampasi, C., Stamatis, P. & Hens, L. Chemical pesticides and human health: The urgent need for a new concept in agriculture. *Frontiers in Public Health* **4**, 148 (2016).

Gasnier, C. *et al*. Glyphosate-based herbicides are toxic and endocrine disruptors in human cell lines. *Toxicology* **262**, 184-191 (2009).

Baker, B. P., Benbrook, C. M., Iii, E. G. & Benbrook, K. L. Pesticide residues in conventional, integrated pest management (IPM)-grown and organic foods: Insights from three US data sets. *Food Additives and Contaminants* **19**, 427-446 (2002).

Synthetic Fertilizers

(Relates to: Soil health; Compounds that can be harmful to humans)

Brandt, K., Leifert, C., Sanderson, R. & Seal, C. J. Agroecosystem management and nutritional quality of plant foods: The case of organic fruits and vegetables. *Critical Reviews in Plant Sciences* **30**, 177-197 (2011).

Elbon, A. & Whalen, J. K. Phosphorus supply to vegetable crops from arbuscular mycorrhizal fungi: a review. *Biological Agriculture & Horticulture* **31**, 73-90 (2015).

Richardson, A. E. *et al*. Plant and microbial strategies to improve the phosphorus efficiency of agriculture. *Plant and Soil* **349**, 121-156 (2011).

Ryan, M. H., McInerney, J. K., Record, I. R. & Angus, J. F. Zinc bioavailability in wheat grain in relation to phosphorus fertilizer, crop sequence and mycorrhizal fungi. *Journal of the Science of Food and Agriculture* **88**, 1208-1216 (2008).

Ward, M. H. *et al*. Drinking water nitrate and human health: An updated review. *International Journal of Environmental Research and Public Health* **15**, 1557 (2018).

Kisby, G. E. & Spence, P. S. Is neurodegenerative disease a long-latency response to early-life genotoxin exposure? *International Journal of Environmental Research and Public Health* **8**, 3889-3921 (2011).

de la Monte, S. M., Neusner, A., Chu, J. & Lawton, M. Epidemiological trends strongly suggest exposures as etiological agents in the pathogenesis of sporadic Alzheimer's disease, diabetes mellitus, and non-alcoholic steatohepatitis. *Journal of Alzheimer's Disease* **17**, 519-529 (2009).

Bioactive Compost, Biochar & Other Soil Amendments
(Relates to: Soil health)

Chaudhary, S., Vaish, B., Singh, R. P., & Prasad, V. Bioactive Compost: An Approach for Managing Plant Growth in Environmentally Stressed Soils. In: *New Frontiers in Stress Management for Durable Agriculture* (eds. Rakshit, A., Singh, H., Singh, A., Singh, U., Fraceto, L.) 257-267 (Springer, 2020).

Compost for Soil Regeneration: Johnson-Su Composting Bioreactor. *Regeneration International*. https://regenerationinternational.org/bioreactor.

Singh Yadav, S. P. *et al*. Biochar application: A sustainable approach to improve soil health. *Journal of Agriculture and Food Research* **11**, 100498 (2023).

Mousavi, S. M., Srivastava, A. K. & Cheraghi, M. Soil health and crop response of biochar: An updated analysis. *Archives of Agronomy and Soil Science* **69**, 1-26 (2022).

Kavitha, B. *et al*. Benefits and limitations of biochar amendments in agricultural soils: A review. *Journal of Environmental Management* **227**, 146-154 (2018).

Ennis, C. J., Evans, A. G., Islam, M., Ralebitso-Senior, T. K. & Senior, E. Biochar: Carbon sequestration, land remediation, and impacts on soil microbiology. *Critical Reviews in Environmental Science and Technology* **42**, 2311-2364 (2012).

Calvo, P., Nelson, L. & Kloepper, J. W. Agricultural uses of plant biostimulants. *Plant and Soil* **383**, 3-41 (2014).

Hamid, B. *et al*. Bacterial plant biostimulants: A sustainable way towards improving growth, productivity, and health of crops. *Sustainability* **13**, 2856 (2021).

Lingua, G. *et al*. Arbuscular mycorrhizal fungi and plant growth-promoting pseudomonads increases anthocyanin concentration in strawberry fruits (*Fragaria x ananassa* var. Selva) in conditions of reduced fertilization. *International Journal of Molecular Sciences* **14**, 16207-16225 (2013).

Lombardo, S. *et al*. Mycorrhizal inoculation improves mineral content of organic potatoes grown under calcareous soil. *Agriculture* **11**, 333 (2021).

Rana, A., Joshi, M., Prasanna, R., Shivay, Y. S. & Nain, L. Biofortification of wheat through inoculation of plant growth promoting rhizobacteria and cyanobacteria. *European Journal of Soil Biology* **50**, 118-126 (2012).

Foliar Spray
(Relates to: Plant or animal management practices)

Kannan, S. Foliar Fertilization for Sustainable Crop Production. In: *Genetic Engineering, Biofertilisation, Soil Quality and Organic Farming* (ed. Lichtfouse, E.) 371-402 (Springer, 2010).

Kempf, J. Organic Foliar Applications Accelerate Growth. *Acres U.S.A.* https://www.ecofarmingdaily.com/build-soil/soil-inputs/fertilizers/using-organic-foliar-applications/ (2019).

Wang, K-H., DuPonte, M. & Chang, K. Use of Korean natural farming for vegetable crop production in Hawai'i. *Hanai'Ai/The Food Provider*. https://gms.ctahr.hawaii.edu/gs/handler/getmedia.ashx?moid=4372&dt=3&g=12 (2013).

Sunlight
(Relates to: Plant or animal management practices)

Ntagkas, N., Woltering, E., Nicole, C., Labrie, C. & Marcelis, L. F. M. Light regulation of vitamin C in tomato fruit is mediated through photosynthesis. *Environmental and Experimental Botany* **158**, 180-188 (2019).

Harborne, J. B. & Williams, C. A. Advances in flavonoid research since 1992. *Phytochemistry* **55**, 481-504 (2000).

Feed Type
(Relates to: Plant or animal management practices)

Provenza, F. D., Kronberg, S. L. & Gregorini, P. Is grassfed meat and dairy better for human and environmental health? *Frontiers in Nutrition* **6**, 26 (2019).

Davis, H., Chatzidimitriou, E., Leifert, C. & Butler, G. Evidence that forage-fed cows can enhance milk quality. *Sustainability* **12**, 3688 (2020).

Benbrook, C. M., Davis, D. R. & Heins, B. Enhancing the fatty acid profile of milk through forage-based rations, with nutrition modeling of diet outcomes. *Food Science & Nutrition* **6**, 681-700 (2018).

Barca, J. *et al.* Milk fatty acid profile from cows fed with mixed rations and different access time to pastureland during early lactation. *Journal of Animal Physiology and Animal Nutrition* **102**, 620-629 (2018).

Carrillo, J. A. *et al*. Integrated metabolomic and transcriptome analyses reveal finishing forage affects metabolic pathways related to beef quality and animal welfare. *Scientific Reports* **6**, 25948 (2016).

Provenza, F. D. *et al*. The value to herbivores of plant physical and chemical diversity in time and space. *Crop Science* **47**, 382-398 (2007).

Antibiotics & Hormones
(Relates to: Soil health; Plant or animal management practices; Compounds that can be harmful to humans)

Martin, M. J., Thottathil, S. E. & Newman, T. B. Antibiotics overuse in animal agriculture: A call to action for health care providers. *American Journal of Public Health* **105**, 2409-2410 (2015).

Moyer, M. W. How Drug-Resistant Bacteria Travel from the Farm to Your Table. *Scientific American.* https://www.scientificamerican.com/article/how-drug-resistant-bacteria-travel-from-the-farm-to-your-table/ (2016).

Stop Using Antibiotics in Healthy Animals to Prevent the Spread of Antibiotic Resistance. *World Health Organization*. who.int/news/item/07-11-2017-stop-using-antibiotics-in-healthy-animals-to-prevent-the-spread-of-antibiotic-resistance (2017).

Smith, P. A. Antibiotics May Compromise Manure's Carbon-Fixing Effects. *Scientific American*. https://www.scientificamerican.com/article/antibiotics-may-compromise-manures-carbon-fixing-effects/ (2020).

Cox, L. M. Antibiotics shape microbiota and weight gain across the animal kingdom. *Animal Frontiers* **6**, 8-14 (2016).

Senthil Kumar, V., Rajan, C., Divya, P. & Sasikumar, S. Adverse effects on consumer's health caused by hormones administered in cattle. *International Food Research Journal* **25**, 1-10 (2018).

Watson, R. EU says growth hormones pose health risk. *British Medical Journal* **318**, 1442 (1999).

Hormones in Meat. *European Commission*. https://food.ec.europa.eu/safety/chemical-safety/hormones-meat_en.

Broocks, A., Rolf, M. & Place, S. Growth Promotants Reduce Beef's Environmental Impact. *Oklahoma State University Extension*. https://extension.okstate.edu/fact-sheets/growth-promotants-reduce-beefs-environmental-impact.html (2017).

PFAS, Heavy Metals & Other Soil Toxins
(Relates to: Soil health; Compounds that can be harmful to humans)

Brusseau, M. L., Anderson, R. H. & Guo, B. PFAS concentrations in soils: Background levels versus contaminated sites. *Science of the Total Environment* **740**, 140017 (2020).

Sandeep, G., Vijayalatha, K. R. & Anitha, T. Heavy metals and its impact in vegetable crops. *International Journal of Chemical Studies* **7**, 1612-1621 (2019).

Manzoor, J., Sharma, M. & Wani, K. A. Heavy metals in vegetables and their impact on the nutrient quality of vegetables: A review. *Journal of Plant Nutrition* **41**, 1744-1763 (2018).

Duruibe, J. O., Ogwuegbu, M. O. C. & Egwurugwu, J. N. Heavy metal pollution and human biotoxic effects. *International Journal of Physical Sciences* **2**, 112-118 (2007).

Post-Harvest Crop Management

Castrejón, A. D. R., Eicholz, I., Rohn, S., Kroh, L. W. & Huyskens-Keil, S. Phenolic profile and antioxidant activity of highbush blueberry (*Vaccinium corymbosum* L.) during fruit maturation and ripening. *Food Chemistry* **109**, 564-572 (2008).

Özcan, M. M. *et al*. The effect of harvest time and varieties on total phenolics, antioxidant activity and phenolic compounds of olive fruit and leaves. *Journal of Food Science and Technology* **56**, 2373-2385 (2019).

Oney-Montalvo, J. E., Avilés-Betanzos, K. A., Ramírez-Rivera, E. de J., Ramírez-Sucre, M. O. & Rodríguez-Buenfil, I. M. Polyphenols content in capsicum Chinese fruits at different harvest times and their correlation with the antioxidant activity. *Plants* **9**, 1394 (2020).

Ariza, M. *et al*. Effect of harvest time on functional compounds and fruit antioxidant capacity in ten strawberry cultivars. *Journal of Berry Research* **5**, 71-80 (2015).

Connor, A. M., Luby, J. J., Hancock, J. F., Berkheimer, S. & Hanson, E. J. Changes in fruit antioxidant activity among blueberry cultivars during cold-temperature storage. *Journal of Agricultural and Food Chemistry* **50**, 893-898 (2002).

Zhang, Y., Truzzi, F., D'Amen, E. & Dinelli, G. Effect of storage conditions and time on the polyphenol content of wheat flours. *Processes* **9**, 248 (2021).

Bhat, R. & Stamminger, R. Impact of combination treatments of modified atmospheric packaging and refrigeration on the status of antioxidants in highly perishable strawberries: Preservation of strawberries. *Journal of Food Process Engineering* **39**, 121-131 (2016).

See Robinson, J. (2013) under VARIETAL & BREED.

Capino, A. & Farcuh, M. Ethylene and the regulation of fruit ripening. *University of Maryland Extension*. https://extension.umd.edu/resource/ethylene-and-regulation-fruit-ripening (2022).

Asami, D. K., Hong, Y.-J., Barrett, D. M. & Mitchell, A. E. Comparison of the total phenolic and ascorbic acid content of freeze-dried and air-dried marionberry, strawberry, and corn grown using conventional, organic, and sustainable agricultural practices. *Journal of Agricultural and Food Chemistry* **51**, 1237-1241 (2003).

Cappeli, A., Oliva, N. & Cini, E. Stone milling versus roller milling: A systematic review of the effects on wheat flour quality, dough rheology, and bread characteristics. *Trends in Food Science & Technology* **97**, 147-155 (2020).

Decker, E. A., Rose, D. J., & Stewart, D. Processing of oats and the impact of processing operations on nutrition and health benefits. *British Journal of Nutrition* **112**, S58-S64 (2014).

Debelo, H., Li, M., & Ferruzzi, M. G. Processing influences on food polyphenol profiles and biological activity. *Current Opinion in Food Science* **32**, 90-102 (2020).

General Human Health & Nutrition

Hepperly, P. R., Omondi, E. & Seidel, R. Soil regeneration increases crop nutrients, antioxidants and adaptive responses. *MOJ Food Processing & Technology* **6**, 196-203 (2018).

Montgomery, D. R., Biklé, A., Archuleta, R., Brown, P. & Jordan, J. Soil health and nutrient density: Preliminary comparison of regenerative and conventional farming. *PeerJ* **10**, e12848 (2022).

Wagner, M. & Omondi, E. Organic Oats More Nutrient Dense than Conventional. *Rodale Institute*. http://rodaleinstitute.org/science/articles/nutrient-density-comparison-between-organic-and-conventionally-grown-oats/ (2016).

Mitchell, A. E. *et al*. Ten-year comparison of the influence of organic and conventional crop management practices on the content of flavonoids in tomatoes. *Journal of Agricultural and Food Chemistry* **55**, 6154-6159 (2007).

Ren, F. *et al*. Higher antioxidant activity, total flavonols, and specific quercetin glucosides in two different onion (Allium cepa L.) varieties grown under organic production: Results from a 6-year field study. *Journal of Agricultural and Food Chemistry* **67**, 3068 (2019).

Barański, M. *et al*. Higher antioxidant and lower cadmium concentrations and lower incidence of pesticide residues in organically grown crops: a systemic literature review and meta-analysis. *British Journal of Nutrition* **112**, 794-811 (2014).

van Vliet, S., Provenza, F. D. & Kronberg, S. L. Health-promoting phytonutrients are higher in grass-fed meat and milk. *Frontiers in Sustainable Food Systems* **4**, 555426 (2021).

See Cobb, A. B. *et al*. (2016) under HERITAGE, HYBRID, GMO, BIOFORTIFIED, REGIONAL & ORGANIC SEEDS.

See Elbon, A. & Whalen, J. K. (2014) under HERITAGE, HYBRID, GMO, BIOFORTIFIED, REGIONAL & ORGANIC SEEDS.

See Jacoby, R., Peukert, M., Succurro, A., Koprivova, A. & Kopriva, S. (2017) under HERITAGE, HYBRID, GMO, BIOFORTIFIED, REGIONAL & ORGANIC SEEDS.

LeZaks, D. & Ellerton, M. The Regenerative Agriculture and Human Health Nexus: Insights from Field to Body. *Croatan Institute* http://croataninstitute.org/wp-content/uploads/2021/09/RegenAg_HumanHealth_2021.pdf (2021).

Moyer, J. *et al*. The Power of the Plate: The Case for Regenerative Organic Agriculture in Improving Human Health. https://rodaleinstitute.org/wp-content/uploads/Rodale-Institute-The-Power-of-the-Plate-The-Case-for-Regenerative-Organic-Agriculture-in-Improving-Human-Health.pdf (2020).

Mayer, E. *The Gut-Immune Connection*. (HarperCollins Publishers, 2021).

Spector, T. *Food for Life: The New Science of Eating Well*. (Penguin Random House, 2022).

Shiva, V. & Singh, V. Health per Acre: Organic Solutions to Hunger and Malnutrition. *Navdanya International*. https://navdanyainternational.org/wp-content/uploads/2017/07/Health-Per_Acre.pdf (2016).

2020 Data Report. *The Bionutrient Institute*. https://www.bionutrientinstitute.org/2020datareport (2020).

Small Grains Report. *The Bionutrient Institute*. https://www.bionutrientinstitute.org/2020grainsreport (2021).

Micronutrients

Lehmann, A., Versoglou, S. D., Leifheit, E. F. & Rilling, M. C. Arbuscular mycorrhizal influence on zinc nutrition in crop plants—a meta-analysis. *Soil Biology and Biochemistry* **69**, 123-131 (2014).

Dakora, F. D. & Phillips, D. A. Root exudates as mediators of mineral acquisition in low-nutrient environments. *Plant and Soil* **245**, 35-47 (2002).

Berendsen, R. L., Pieterse, C. M. J. & Bakker, P. A. H. M. The rhizosphere microbiome and plant health. *Trends in Plant Science* **17**, 478-486 (2012).

Lambert, D. H., Baker, D. E. & Cole, H. Jr. The role of mycorrhizae in the interactions of P with Zn, Cu and other elements. *Soil Science Society of America Journal* **43**, 976-980 (1979).

Marschner, H. & Dell, B. Nutrient uptake in mycorrhizal symbiosis. *Plant and Soil* **159**, 89-102 (1994).

Adak, A. *et al*. Micronutrient enrichment mediated by plant-microbe interactions and rice cultivation practices. *Journal of Plant Nutrition* **39**, 1216-1232 (2016).

Rengel, Z., Batten, G. D. & Crowley, D. E. Agronomic approaches for improving the micronutrient density in edible portions of field crops. *Field Crops Research* **60**, 27-40 (1999).

Gosling, P., Hodge, A., Goodlass, G. & Bending, G. D. Arbuscular mycorrhizal fungi and organic farming. *Agriculture, Ecosystem & Environment* **113**, 17-35 (2006).

Beelman, R. B. *et al*. Health consequences of improving the content of ergothioneine in the food supply. *FEBS Letters* **596**, 1231-1240 (2022).

White, J., Kingsley, K., Verma, S. & Kowalski, K. Rhizophagy cycle: An oxidative process in plants for nutrient extraction from symbiotic microbes. *Microorganisms* **6**, 95 (2018).

Phytonutrients

Isah, T. Stress and defense responses in plant secondary metabolites production. *Biological Research* **52**, 39 (2019).

Agnolucci, M. *et al*. Health-promoting properties of plant products: The role of mycorrhizal fungi and associated bacteria. *Agronomy* **10**, 1864 (2020).

Selosse, M.-A., Bessis, A. & Pozo, M. J. Microbial priming of plant and animal immunity: symbionts as developmental signals. *Trends in Microbiology* **22**, 607–613 (2014).

Postler, T. S. & Ghosh, S. Understanding the holobiont: How microbial metabolites affect human health and shape the immune system. *Cell Metabolism* **26**, 110-130 (2017).

Wan, M. L. Y., Co, V.A. & El-Nezami, H. Dietary polyphenol impact on gut health and microbiota. *Critical Reviews in Food Science and Nutrition* **61**, 690-711 (2021).

Del Bo', C. *et al*. A polyphenol-rich dietary pattern improves intestinal permeability, evaluated as serum zonulin levels, in older subjects: The MaPLE randomised controlled trial. *Clinical Nutrition* **40**, 3006-3018 (2021).

Pei, R., Liu, X. & Bolling, B. Flavonoids and gut health. *Current Opinions in Biotechnology* **61**, 153-159 (2020).

Martel, J. *et al*. Hormetic effects of phytochemicals on health and longevity. *Trends in Endocrinology & Metabolism* **30**, 335-346 (2019).

Rosier, C. L. *et al*. Validation of low-cost reflectometer to identify phytochemical accumulation in food crops.

Fatty Acids

Thesing, C.S., Bot, M., Milaneschi, Y., Giltay, E. J. & Penninx, B. W. J. H. Omega-3 polyunsaturated fatty acid levels and dysregulations in biological stress systems. *Psychoneuroendocrinology* **97**, 206-215 (2018).

Costantini, L., Molinari, R., Farinon, B. & Merendino, N. Impact of omega-3 fatty acids on the gut microbiota. *International Journal of Molecular Sciences* **18**, 2645 (2017).

Patterson, E., Wall, R., Fitzgerald, G. F., Ross, R. P. & Stanton, C. Health implications of high dietary omega-6 polyunsaturated fatty acids. *Journal of Nutrition and Metabolism* **2012**, 539426 (2012).

Viladomiu, M., Hontecillas, R. & Bassaganya-Riera, J. Modulation of inflammation and immunity by dietary conjugated linoleic acid. *European Journal of Pharmacology* **785**, 87-95 (2016).

Other Human Health & Nutrition

Wassermann, B., Henry, M. & Gabriele, B. An apple a day: Which bacteria do we eat with organic and conventional apples? *Frontiers in Microbiology* **10**, 1629 (2019).

Sonnenburg, E. D. & Sonnenburg, J. L. Starving our microbial self: The deleterious consequences of a diet deficient in microbiota-accessible carbohydrates. *Cell Metabolism* **20**, 779-786 (2014).

Banarjee, S. & van der Heijden, M. G. A. Soil microbiomes and one health. *Nature Reviews Microbiology* **21**, 6-20 (2022).

Hirt, H. Healthy soils for healthy plants for healthy humans. *EMBO Reports* **21**, e51069 (2020).

Flandroy, L. *et al*. The impact of human activities and lifestyles on the interlinked microbiota and health of humans and of ecosystems. *Science of the Total Environment* **627**, 1018-1038 (2018).

Barabási, A. L., Menichetti, G. & Loscalzo, J. The unmapped chemical complexity of our diet. *Nature Food* **1**, 33-37 (2020).

Sandström, B. Micronutrient interactions: effects on absorption and bioavailability. *British Journal of Nutrition* **85**, S181 (2001).

Gibson, R. S. The role of diet- and host-related factors in nutrient bioavailability and thus in nutrient-based dietary requirement estimates. *Food and Nutrition Bulletin* **28**, S77-100 (2007).

Mozaffarian, D., Rosenberg, I. & Uauy, R. History of modern nutrition science–implications for current research, dietary guidelines, and food policy. *BMJ* **361**, k2392 (2018).

Combs, G. F. & McClung, J. P. *The Vitamins: Fundamental Aspects in Nutrition and Health, 6th Edition*. (Academic Press, 2022).