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# Soil Health and Nutrient Density: Beyond Organic vs. Conventional Farming

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Controversy has long surrounded the question of nutritional differences between crops grown organically or using now-conventional methods, with studies dating back to the 1940s showing that farming methods can affect the nutrient density of crops. More recent studies have shown how reliance on tillage and synthetic nitrogen fertilizers influence soil life, and thereby soil health, in ways that can reduce mineral micronutrient uptake by and phytochemical production in crops. While organic farming tends to enhance soil health and conventional practices degrade it, relying on tillage for weed control on both organic and conventional farms degrades soil organic matter and can disrupt soil life in ways that reduce crop mineral uptake and phytochemical production. Conversely, microbial inoculants and compost and mulch that build soil organic matter can increase crop micronutrient and phytochemical content on both conventional and organic farms. Hence, agronomic effects on nutritional profiles do not fall out simply along the conventional vs. organic distinction, making the effects of farming practices on soil health a better lens for assessing their influence on nutrient density. A review of previous studies and meta-studies finds little evidence for significant differences in crop macronutrient levels between organic and conventional farming practices, as well as substantial evidence for the influence of different cultivars and farming practices on micronutrient concentrations. More consistent differences between organic and conventional crops include that conventional crops contain greater pesticide levels, whereas organically grown crops contain higher levels of phytochemicals shown to exhibit health-protective antioxidant and anti-inflammatory properties. Thus, part of the long-running controversy over nutritional differences between organic and conventional crops appears to arise from different definitions of what constitutes a nutrient—the conventional definition of dietary constituents necessary for growth and survival, or a broader one that also encompasses compounds beneficial for maintenance of health and prevention of chronic disease. For assessing the effects of farming practices on nutrient density soil health adds a much needed dimension—the provisioning of micronutrients and phytochemicals that support human health.

**Keywords: soil health, organic, conventional, nutrient-density, farming**

## INTRODUCTION

In the Twentieth century, now-conventional agronomic practices of frequent mechanical tillage and copious chemical fertilizer and pesticide applications displaced traditional practices incorporating cover crops and diverse crop rotations. Since the 1940s, mainstream agronomic research has focused primarily on pursuit of higher yields, greater crop protein content, and chemical pest control. However, recent recognition of the role of soil life in influencing the nutrient density of crops raises questions around whether adoption of now-conventional practices inadvertently shortchanged crops on micronutrients and phytochemicals important for human health (Montgomery and Biklé, 2016).

Soil erosion and degradation of soil fertility have long been serious concerns among farmers and natural philosophers, with efforts to improve soils in the United States dating back to colonial times drawing on practices independently adopted by indigenous peoples around the world (Montgomery, 2007). Human conceptions of soil fertility evolved from a divinely endowed blessing in ancient times to an intrinsic feature imposed by climate and geology, with contingent aspects subject to radical modification through farming practices and soil husbandry (Uphoff et al., 2013). Most recently, the conventional view of crop mineral nutrition is being reframed around biologically mediated plant-soil interactions (Briat et al., 2020).

In this sense, soil health reflects both biotic and abiotic (chemical and physical) aspects of the soil. Soil health is defined as the capacity of soil to function as a living ecosystem that sustains plants, animals, and people (Doran, 2002; Lehmann et al., 2020). There are two primary ways that farming practices influence soil health and quality: the physical loss of topsoil (erosion) and loss of soil organic matter, soil structure, and soil life (soil degradation) (Bünemann et al., 2018). Organic and conventional farming practices alike have seriously eroded and degraded soils in ancient and modern societies that relied on frequent tillage (Montgomery, 2007). The potential for now-conventional farming practices to affect communities of soil life in ways that matter to crop production and nutritional profiles was recognized in the mid-twentieth century (Howard, 1940; Balfour, 1943), although lack of mechanistic understanding hindered mainstream acceptance of such assertions. Since then, advances in soil ecology revealed that soil health plays a major, though long-neglected role in building and sustaining soil fertility (Uphoff et al., 2013)—and point to other linkages between soil health and the nutritional qualities of food.

To date, agriculture has degraded as much as one-third of the world's potential farmland (Pimental et al., 1995), and according to a recent UN report humanity remains on track to degrade another third of global agricultural production over the course of this century (FAO, 2015). Over the past century, topsoil was completely eroded from about a third of the US Corn Belt, reducing the region's overall crop yields by about 6% despite massive applications of synthetic chemical fertilizers (Thaler et al., 2021). Averaged across North America, post-colonial farming practices reduced soil organic matter by roughly half (Baumhardt et al., 2015) and land degradation already adversely affects the well-being of more than 3 billion people globally (IPBES, 2018). That soil health is central to nutrient cycling and delivery to crops through microbial symbioses that bolster plant health and defense (Montgomery and Biklé, 2016; Lehmann et al., 2020) indicates a likely potential for substantial agricultural impacts on crop micronutrient and phytochemical content.

Concerns over the effects of now-conventional farming practices on the nutrient density of food were noted as a result of experiments in the 1920s and 1930s centered on feeding experiments involving rats and the vitamin content of grains (McCarrison, 1924; Rowlands and Wilkinson, 1930). Since then conflicting results and claims flowed from studies employing different metrics and definitions as to what constitutes a nutrient, and therefore nutrition. Recently, long-standing concerns centered on micronutrients—vitamins and trace minerals—expanded to include phytochemicals that influence human health but are not conventionally considered nutrients (Craig, 1997; Zhang et al., 2015).

The nutrient density of food can be quantified in terms of the amount of nutrients per calorie—the ratio of nutritional value to energy intake (Drewnowski, 2009). In practice, nutrients are generally defined as substances essential for growth and maintenance of life. These include macronutrients needed in quantity and micronutrients for which small amounts are essential for normal metabolism or as key coenzymes and cofactors for proteins. While nutritional science has long focused on determining adequate intake levels for different macro- and micronutrients, recommended dietary intake levels have not been established for phytochemicals like polyphenols, flavonoids, and anthocyanins now recognized as having significant protective antioxidant and anti-inflammatory effects relevant to human health (Krzyzanowska et al., 2010). Yet studies over the past several decades clearly established that soil life influences both mineral uptake and phytochemical production in numerous crops (e.g., Lambert et al., 1979; Marschner and Dell, 1994; Miller, 2000; Jansa et al., 2006; Ryan et al., 2008; White and Broadley, 2009; Zhang et al., 2012; Lehmann et al., 2014; Adak et al., 2016; Konecny et al., 2019).

This paper broadly reviews advances in key aspects of understanding how farming practices that affect soil health influence nutrient density through disrupting or cultivating beneficial soil life. In light of these connections the paper also re-examines studies of differences in crop nutritional profiles in conventional and organic farming systems and suggests that the effects of farming practices on soil health provide a better lens for assessing impacts on the nutritional composition of food crops.

## SOIL HEALTH, SOIL LIFE, AND FARMING PRACTICES

Conventional metrics for assessing soil quality have primarily focused on physical and chemical factors that support crop production, yet growing awareness of the importance of soil ecology and the diversity and abundance of soil life is reshaping agronomic thought to embrace enhancing and sustaining soil health as a fundamental agronomic goal. Along with traditional physical and chemical factors (e.g., bulk density and pH), soil organic matter content and soil biodiversity are recognized as key aspects of soil health (Lehmann et al., 2020). While creating quantitative soil health indices remains challenging, due to varying regional controls on soil properties and life, promoting farming practices that promote soil health is increasingly seen as central to developing sustainable farming systems (Montgomery, 2017).

As reviewed below, regular tillage and liberal applications of synthetic nitrogen fertilizers influence soil life in ways that alter the abundance and community composition of soil bacteria, fungi, and larger life forms, like earthworms. Specifically, tillage and chemical fertilizers affect soil health through reducing soil organic matter and the diversity and abundance of soil life. Such changes can influence nutrient cycling, crop mineral uptake, and phytochemical production.

Tillage—the primary means of weed control on most organic and conventional farms—typically degrades soil organic matter by stimulating a burst of microbial activity. A 1995 review of more than 100 peer-reviewed papers found that tillage profoundly disturbed soil food webs (Wardle, 1995). Perhaps the most intuitive impact of tillage is on earthworms. Tillage affects the abundance and community composition of earthworms in both organic and conventional farming systems (Crittenden et al., 2014). A recent review of long-term farming trials—some run for over a century—found consistent losses of more than half of the total biomass of worms on conventional fields (Blakemore, 2018). And a 20-year comparison of soil quality under conventional and no-till farming in New Zealand found that no-till fields had almost as many worms as found in unplowed pasture, whereas conventionally tilled fields had virtually no worms and a third to half the microbes of unplowed fields (Ross et al., 2002). Likewise, a recent South African study found that earthworm abundance and diversity were higher under no-till with residue retention and diverse crop rotation than under conventional tillage (Mcinga et al., 2020).

Tillage decreases the diversity of soil fungi and bacteria and particularly disrupts root-like fungal hyphae, reducing deliveries of mineral elements to plants from fungal symbionts (Anderson et al., 2017). In general, plowing shifts soil life toward more bacterially dominated communities with a lower ratio of fungal to bacterial biomass (Jansa et al., 2006). So bacteria tend to play a dominant role in decomposing organic matter in tilled systems, whereas fungi and earthworms play bigger roles in no-till systems (Hendrix et al., 1986). In changing the composition of soil microbial communities, different farming systems affect soil life in ways that can influence nutrient cycling through altering crop-microbe symbioses. And because tillage results in a burst of rapid bacterially-driven degradation of soil organic matter, fields in tropical regions typically can be tilled economically for less than a decade without supplemental fertilization, whereas it can take more than half a century for comparable loss and dependence on supplemental fertilization to develop in temperate grassland soils (Tiessen et al., 1994). In contrast, a recent meta-analysis of studies in the U.S. found that reduced tillage intensity improves soil structure (Nunes et al., 2020a).

Fertilizer use also affects soil life. Synthetic nitrogen fertilizers, for example, are known to reduce the abundance and diversity of mycorrhizal fungi (Egerton-Warburton and Allen, 2000). Field-scale and experimental studies show that high nitrogen fertilizer use selects for less mutualistic fungi (Johnson, 1993; Corkidi et al., 2002) over mycorrhizal fungi that preferentially take up minerals like zinc and phosphorous and deliver them to crops (Bolan, 1991; Antunes et al., 2012). The effects of mycorrhizal fungi on crop uptake of zinc are well-established, with a meta-analysis of 104 studies that reported on 263 field trials finding that mycorrhizae increased zinc concentrations by up to almost a third across a range of crops (Lehmann et al., 2014). In other words, disrupting soil microbial communities affects crop mineral uptake.

Most plants have two pathways for acquiring minerals, a direct pathway of passive adsorption taking up minerals dissolved in the water that roots pull up from the soil, and a second, more active pathway that runs through fungal partnerships (Sawers et al., 2006). Different genes govern these pathways. Using phosphorous as an example, particular genes up-regulate root exudate production when this nutrient is scarce and down-regulate it when phosphorus is abundant (Konecny et al., 2019). This suggests that crops receiving a steady diet of chemical fertilizers slack off on recruiting fungal partners, resulting in lower mineral uptake (Rengel et al., 1999; Ryan et al., 2008; Zhang et al., 2012).

Numerous studies have documented that nitrogen-rich fertilizers reduce phytochemical production related to plant defense, like the phenolic compounds in foliage (Brandt et al., 2011). Conversely, decreased nitrogen availability generally increases the content of defensive compounds in crops, enhancing disease resistance at the expense of growth (Brandt et al., 2011). Nutrient-poor environments increase the production of phenolic compounds, whereas nutrient-rich environments—like nitrogen-fertilized soils—decrease crop phenolic production (Reeve et al., 2016).

Numerous studies show that farming practices strongly affect two key aspects of soil health—soil organic matter and the community composition of soil life. A 12-year comparison of conventionally tilled and no-till fields showed that no-till farming resulted in higher soil organic matter levels, greater microbial biomass, and greater levels of plant-available zinc in the soil (Nunes et al., 2018). In addition, introducing a cover crop increased the amount of plant-available iron in the soil. A review of 54 field studies found that less intensive tillage combined with cover cropping greatly increased mycorrhizal colonization of crop roots (Bowles et al., 2016). In general, microbial diversity declines under tillage (Sengupta and Dick, 2015), whereas minimal-till or no-till methods increase microbial biomass and enzyme activity (Zuber and Villamil, 2016). Growing cover crops further increases soil microbial biomass (McDaniel et al., 2014) and diversity (Verzeaux et al., 2016).

Crop rotation—or the lack of it—also affects the diversity and composition of mycorrhizal fungi (Jansa et al., 2006). Experiments at the University of Kentucky in the 1990s showed that crop rotations dramatically alter the community composition of mycorrhizal fungi, with greater fungal richness and diversity in rotated crops than continuously cultivated ones (Hendrix et al., 1995). Depending on which crops were grown in what order, the soil microbial community shifted rapidly from one crop to the next in ways that promoted either mutualistic or pathogenic interactions.

The combination of no-till and cover crops increases both soil organic matter and soil health. An analysis of over seven thousand observations from eight U.S. regions found that combining reduced tillage with planting cover crops increased soil organic matter levels and that diversified cropping systems attained the highest levels, although results varied regionally with differences in precipitation and temperature (Nunes et al., 2020b). Likewise, a global meta-analysis of organic farming systems found that the combination of conservation tillage, cover cropping, and organic amendments greatly enhanced soil health through increased soil organic matter and microbial biomass (Crystal-Ornelas et al., 2021).

Organic practices generally increase both microbial diversity and abundance despite typical reliance on tillage for weed control. For example, a national comparison of farms across the United States found that organic farming supported healthier soils with higher soil organic matter content than conventional farming practices (Ghabbour et al., 2017). An analysis of 56 studies from around the world reported direct comparisons of paired conventional and organically farmed fields with the same soil type over an average of 16-years (Lori et al., 2017). Organically-farmed soils hosted substantially greater microbial biomass, microbial activity, and diversity than conventionally farmed soils. Specifically, microbial biomass carbon and nitrogen were 41 and 51% higher, respectively, on the organic plots. The organic plots also had 32–74% more microbial enzyme activity. Most of the studies reviewed found significant differences in the composition of the soil community, with organic farming practices increasing the abundance and activity of soil life (Lori et al., 2017).

A recent review concluded that studies demonstrate convincing evidence that livestock manure enhances soil health and crop growth, although the benefits depend on the properties of the manure as well as specific farming practices, soil type, and regional climate (Rayne and Aula, 2020). Likewise, a recent study found that using clover as green manure in conjunction with nitrogen fertilizers improved soil health, grain yields, and grain nutritional content (Shabir et al., 2020). Recent studies also show that diverse cover crops enhance soil health (Saleem et al., 2020) and that compost (De Corato, 2020) and other soil health building practices (Abawi and Widmer, 2000) suppress soil-borne plant pathogens.

A 14-year French study that tracked the response of soil life to both conventional and organic farming also addressed conservation agriculture practices that minimized but did not eliminate tillage and agrochemical use (Henneron et al., 2015). Both the conventional and organic fields were plowed 3 out of every 4-years. The conservation agriculture system used no-till methods and grass cover crops, and applied pesticides only upon exceeding an economic damage threshold. Relative to conventional farming, the abundance and biomass of soil life increased under both organic farming and conservation agriculture—visible soil life (earthworms and arthropods) increased two to twenty-five-fold and microorganisms (bacteria and fungi) increased by 30–70%. While conservation agriculture practices increased soil life across the board, organic practices mainly increased bacteria and earthworm populations.

Conventional farming practices also influence the production of phytochemicals in crops. For example, synthetic nitrogen fertilizers generally reduce the amount of phenolic compounds in foliage (Brandt et al., 2011). In particular, numerous studies have documented that nitrogen-rich fertilizers reduce the production of phytochemicals related to plant defense (Brandt et al., 2011). In effect, loading up soils with soluble synthetic nitrogen fertilizers presents plants with a nutrient windfall that promotes building biomass over making defensive compounds, like phytochemicals.

Plants actively shape their microbiome through the release of root exudates to help repel pathogens and assist in nutrient acquisition and phytochemical production (Berendsen et al., 2012). Recent demonstration that the soil microbiome affects root exudate production and that this, in turn, influences soil conditions (Korenblum et al., 2020) indicates that farming practices that affect soil community composition affect root exudates in ways that can influence mineral uptake and phytochemical production that affects crop health and defense. For example, diversifying the crops grown in a field can increase their mineral density, and intercropping diverse plants together in the same field, as is common in parts of Asia, Africa, and Latin America, can increase mineral density in crops (Zuo and Zhang, 2009; Xue et al., 2016). So it goes to reason that farming practices that affect soil health and the abundance and diversity of soil communities could influence the micronutrient and phytochemical content of food.

It is now recognized that environmental influences are as important as genetic variation in controlling mineral and phytochemical levels in crops, which can vary over a hundred-fold, and that the manner in which crops are cultivated and livestock are raised influences their levels in our food (Johansson et al., 2014). Because soil life can affect crop micronutrient and phytochemical content, plowing fields and relying on synthetic nitrogen fertilizers can disrupt symbiotic partnerships between plants and soil microbiota at the root of crop nutritional profiles. As organic farming tends to rely on tillage for weed control, and conventional farming relies on heavy use of synthetic nitrogen fertilizers, both systems can adversely impact soil life, and thereby mineral uptake and phytochemical production. In this way, soil health defined by the abundance, diversity, and activity of soil life offers a different way to frame understanding the effects of farming practices on the nutritional profile of crops.

Given the findings of the studies discussed above, it is reasonable to hypothesize that in addition to the known effects of crop breeding (Morris and Sands, 2006), microbial community disruption due to degraded soil health contributed to the historical declines of mineral micronutrients and phytochemicals in crops (Mayer, 1997; Davis et al., 2004; White and Broadley, 2005; Ekholm et al., 2007; Davis, 2009). Indeed, evidence for such a connection emerged in the early days of now-conventional practices.

## EARLY STUDIES OF NITROGEN FERTILIZERS

In considering the dietary implications of intensive nitrogen fertilizer use agronomists tended to focus on yields and protein content, especially of grains. As proteins incorporate nitrogen, synthetic nitrogen fertilizers generally increase protein concentrations in grains and pulses (Wang Z.-H. et al., 2008). Although early research on the effects of conventional farming on nutritional quality focused on enhancing dietary protein intake, researchers came to note potential adverse influences of nitrogen fertilizers and other now-conventional farming practices on vitamin content and mineral density long before the microbial roots of such connections were understood (Montgomery and Biklé, 2016).

In the 1940s, for example, studies found that nitrogen and potassium fertilizers decreased calcium uptake by vegetables (Sheets et al., 1944; Wittwer and Goff, 1946). Fertilizing turnip greens with synthetic nitrogen reduced their calcium content by more than a third in four out of five trials in Mississippi (Sheets et al., 1944), and significantly reduced crop iron content in almost half the locations studied (Speirs et al., 1944). Contemporaneous investigations also showed that nitrogen fertilizers reduced the vitamin content of grapefruit juice (Jones et al., 1945) and pepper pods (Petrosini, 1945), but increased the vitamin C content of some crops (Reder et al., 1943).

Overall, early studies reported the mineral content of crops to be quite variable, reflecting among other things the soil it was grown in. Regional studies found that the vitamin C content of turnip greens varied several times more between farms than from the effect of using chemical fertilizers (Reder et al., 1943). The iron content of leafy greens varied two-fold, and turnip greens varied four-fold (Speirs et al., 1944). And while areas with the highest proportion of anemic children were those with low soil iron (Speirs et al., 1944), differences in the iron content of vegetables did not reflect soil iron content (Donelson et al., 1943). So nutrient density did not simply reflect the amount of iron in the soil but how much of it actually got into crops. Nonetheless, the role of synergistic soil fungi generally was overlooked in conventional views of what made mineral elements available to plants.

More recent studies also found large variations in mineral and phytochemical levels between different cultivars of the same crop. For example, calcium levels among varieties of snap beans vary by a factor of two (Quintana et al., 1996). In blackberries mineral micronutrient levels vary greatly among cultivars (Moraes et al., 2021), as do beta-carotene levels in broccoli, and folate (folic acid) levels in red beets vary four-fold among different varieties (Wang and Goldman, 1996; Grusak and DellaPenna, 1999). Likewise, carotenoid levels in papaya cultivars vary severalfold (Laurora et al., 2021) and there are large variations in vitamin C among different varieties of tomatoes (Stevens, 1986) and potatoes (Love et al., 2004). A sampling of 50 different kinds of broccoli found several-fold variations in antioxidant phytochemicals (Kurilich et al., 1999). In other words, different cultivars bred for and grown under different farming systems can exhibit substantial variability in micronutrient and phytochemical density.

Such studies established that the nutrient content of crops varies widely, and effectively eclipsed concern over the effects of farming practice on nutrient density. Indeed, the early recognition of large differences in vitamin and mineral content between crop varieties and farms came to frame the long-conventional view that any effects of tillage or chemical fertilizers would be of little nutritional importance (Hamner, 1945; Somers and Beeson, 1948). Variability due to other factors seemed likely to swamp any effects of farming practices.

Nonetheless, evidence that adopting now-conventional practices influenced the nutritional profile of crops soon emerged. A 1949 study of the mineral content of five vegetables (cabbage, lettuce, snap beans, spinach, and tomatoes) grown in 10 states across the U.S. controlled for different crop varieties to document regional trends and underlying differences in fertilization regimes (Bear et al., 1949). Although the study found large variations in mineral content in each crop it also found that the highest micronutrient values came from areas receiving the least chemical fertilizer. While the study emphasized the conclusion that soil type and climate influenced the mineral composition of crops, the authors also reported that so did fertilization practices.

Another comprehensive study noted nitrogen fertilizer decreased the iron content of turnip greens in 26 of 29 locations across the American South (Speirs et al., 1944). While the size of the effect varied between locations, its direction was consistent. Synthetic nitrogen fertilizer application reduced the iron content of turnip greens by 20% on average, with more nitrogen resulting in less calcium and phosphorus as well. The same study found higher levels of iron in turnip greens grown in soil with more organic matter, and that organic matter was the only soil factor that significantly influenced crop iron content. While chemical fertilizers produced less mineral-dense turnip greens in 8 of 13 field trials across the South (Speirs et al., 1944), the differences were smaller than those reported between different locations. The study did conclude, however, that soil organic matter played a large part in the variation in the iron content of turnip greens (Speirs et al., 1944).

Likewise, the authors of a 1946 study of New Zealand spinach expressed concern about the role of nitrogen fertilizers on the nutritional value of crops (Wittwer and Goff, 1946). The study investigated the effects of soil fertility on dietary sources of calcium and vitamins with "protective" value for health. Researchers grew spinach in the same soil under four different levels of both calcium and nitrogen fertilizers in ten replicated trials. Yields increased with higher rates of nitrogen fertilization, but the vitamin C and phosphorus content of the spinach decreased when grown with more nitrogen, showing that the spinach "became progressively inferior in nutritional value with each additional increment of nitrogen" (Wittwer and Goff, 1946, p. 64).

More recently, a systematic 1993 review found that synthetic nitrogen fertilizers significantly influence the vitamin content of plants (Mozafar, 1993). This global review found substantial evidence that typical high rates of nitrogen fertilizer use greatly decreased the vitamin C content of fruits and vegetables that account for major sources in human diets. Although the magnitude of the vitamin C loss varied for different crops, the decrease could be quite significant, with reported reductions of up to 34% in cabbage and 50% in fruits. It was not simply linear, however. Low application rates of nitrogen fertilizers tended to increase the vitamin C content of crops, whereas typical high rates of nitrogen application greatly decreased vitamin C levels. Nitrogen fertilizers also reduced levels of vitamin E. In addition, the study found that nitrogen fertilizers generally increased the protein and nitrate content of crops. The author considered this combination of reduced vitamin C content and increased nitrate content particularly problematic for human health because vitamin C inhibits the digestive production of carcinogenic compounds from nitrate, cautioning that additional investigation was warranted as nitrate levels could reach "potentially dangerous levels" (Mozafar, 1993).

## NUTRIENT DENSITY

It is generally accepted that organic farming supports more active soil biology (Bulluck et al., 2002; Maeder et al., 2002), and thus greater nutrient cycling, but controversy nonetheless surrounds potential nutritional differences between conventional and organic crops. Divergent study designs and the potential for confounding factors to blur differences helps fuel arguments over the supposed health benefits of organically grown foods. Other factors known to influence nutrient density include the particular crop variety or cultivar, the nature of the soil, and even the weather as a crop grows. The following review of prior studies, however, suggests that evaluating the effects of farming practices on nutrition hinges on whether one limits the definition of nutrients to dietary components essential for growth and survival, or also considers those that support health.

An early comparison of the nutritional value of crops fertilized with either manure or chemical fertilizers was based on 12-years of data on various crops fertilized with farmyard manure, biodynamic compost, or "NPK" (Schuphan, 1974). Crops grown with farmyard manure or compost contained more protein, vitamin C, phosphorus, potassium, and calcium. Remarkably, spinach had 77% more iron. Crops grown with NPK had significantly more nitrate and sodium. Overall, the study concluded that organic practices produced more nutritious crops. Two-years later, a comparison of vegetables grown in the same soil with either organic or "commercial" fertilizers found no difference in major elements (nitrogen, phosphorus, potassium, calcium, and magnesium) (Svec et al., 1976). Such findings set up conflicting narratives around potential differences between organic and conventional foods.

In 1984 a German field trial demonstrated that spinach, Swiss chard, lettuce, and corn fertilized with composted farmyard manure all had significantly lower nitrate and higher vitamin C concentrations than the same crops grown with an equivalent amount of synthetic nitrogen fertilizer (Vogtmann et al., 1984). Complementary experiments showed that higher compost applications decreased the nitrate content several fold in potted spinach despite a higher total supply of nitrogen (Vogtmann et al., 1984). A parallel comparison of nitrate concentrations in lettuce from seven paired conventional and organic farms also found a lot less in organic lettuce (Vogtmann et al., 1984). Several years later the same author reviewed the German agricultural literature and reported conventionally grown foods had far more nitrate and pesticides that those grown using organic farming methods (Vogtmann, 1988).

Another early comparison, published in the *Journal of Applied Nutrition*, reported significant differences in the mineral content of organic and conventional produce purchased in suburban Chicago grocery stores (Smith, 1993). Over a 2-year period organically grown wheat, corn, potatoes, apples, and pears averaged 60–125% more iron, zinc, calcium, phosphorus, magnesium, and potassium relative to conventionally grown counterparts. Since then, a number of studies and meta-studies that compared conventional and organic foods reported a wide range of results and conclusions. Yet, some patterns do emerge from both meta-studies and paired farm and plot experiments.

### Meta-Studies

Meta-studies typically lump a wide range of practices together under the labels of conventional and organic, despite the highly variable physical environments of agricultural settings and the wide range of cultivation methods allowed, and soil health achieved, under both farming systems. Additional factors that complicate assessing differences include the effects of soil type, crop varieties, climate, growing season weather, and different experimental designs between studies. Legacies of past farming practices can matter as well, as published studies comparing conventional and organic crops generally fail to take soil health into account, or how long organic fields had been worked using organic methods.

Nonetheless, a 2001 review of 41 studies reported that on average organic crops had a fifth more to almost a third more vitamin C, iron, and magnesium (Worthington, 2001). Despite differences varying by crop, organic crops consistently had higher overall levels of mineral micronutrients due the author suggested to the influence of soil life. Conversely, conventional crops had more heavy metals. In addition, nitrate levels were significantly higher in conventional foods for almost three-quarters of 176 comparisons. And while organic foods averaged 15% less nitrate, conventional foods had up to eight times more (Worthington, 2001). Similar research in France reported that organic foods contained higher amounts of both minerals and antioxidants than conventionally grown ones (Lairon, 2010).

Other studies also found conventional foods contained more nitrates. A 1997 review concluded that conventionally grown vegetables had "far higher nitrate content than organically produced or fertilized vegetables" (Woese et al., 1997). And a 2005 study found that lower nitrate content and higher vitamin C content consistently differentiated organic from conventional potatoes (Hajslová et al., 2005). The study, however, also reported that both farm-to-farm and year-to-year variability were comparable to the differences between organic and conventional practices.

A 2001 meta-study of micronutrient composition that controlled for both crop variety (cultivar) and soil conditions found higher levels in organic vegetables and legumes than in conventional ones (Hunter et al., 2011), with overall differences of up to 10% in beta-carotene, vitamin C, boron, copper, and zinc. However, those studies that screened for the same cultivar and soil conditions reported that the micronutrient content of organic foods ranged up to almost 50% higher than conventional produce (Hunter et al., 2011).

A widely publicized meta-study along these lines reviewed 223 studies of nutrient levels and contaminants in a wide range of foods (Smith-Spangler et al., 2012). The authors reported that conventional produce consistently had significantly higher levels of pesticide residues and antibiotic resistant bacteria. Conversely, organic produce had higher levels of phenols. As the authors found no significant differences for potassium, calcium, magnesium, and iron or for vitamins A and C, they concluded that organic food was no more nutritious than conventional food, despite the latter containing more pesticides and problematic bacteria, along with fewer health promoting phenols not considered nutrients.

Two-years later, a more comprehensive study in the *British Journal of Nutrition* expanded on the same data set to analyze 343 peer-reviewed publications (Baranski et al., 2014). This exhaustive meta-study concluded that organic crops contained significantly higher concentrations of antioxidants and that conventionally grown crops came with greater levels of pesticide residue and the heavy metal cadmium. The authors estimated that people consuming organically grown foods would take in 20–60% more phytochemicals than if they ate conventional foods.

A 2001 review came to a similar conclusion in finding that plant metabolites related to defense were 10 to 50% higher in organic vegetables than in conventional vegetables (Brandt and Mølgaard, 2001). A follow up meta-analysis a decade later also found significantly more phytochemicals in organic fruits and vegetables (Brandt et al., 2011).

The most recent meta-analysis only looked at studies published after 2000 due to concerns about earlier experimental designs and changing measurement techniques (Fess and Benedito, 2018). Like previous studies, it too found that organically grown crops had higher levels of vitamins and phytochemicals, particularly antioxidants, carotenoids, flavonoids, and phenolic compounds. The review also found conventionally grown fruits and vegetables consistently had higher pesticide levels (Fess and Benedito, 2018), a finding also in line with previous studies (e.g., Pussemier et al., 2006).

## Paired Farm and Long-Term Plot Studies

A number of notable paired farm studies involving multiple farms and long-term plot studies investigated more controlled comparisons of the effects of farming practices on aspects of crop nutrient density. A study from the Burgundy and Jura regions in the late 1980s assessed the effects of organic and conventional fertilizers on the vitamin and mineral content of carrots and celery root (Leclerc et al., 1991). The comparison involved 24 sets of paired farms growing the same crop varieties in the same soil type. The organic carrots had about 12% more beta-carotene and vitamin B1, and the organic celery root had about 11% more vitamin C and less than half the nitrate of their conventional counterparts.

An influential study of strawberries from 13 paired organic and conventional farms in California found that organic ones had significantly higher levels of polyphenols, vitamin C, and antioxidants (Reganold et al., 2010). This comparison also found that conventional strawberries had higher concentrations of phosphorus and potassium. In addition, soil carbon and nitrogen levels were higher in the organically farmed soils, as were microbial biomass and genetic diversity, as well as levels of plant-available iron and zinc.

Comparison of samples from 30 organic and 30 conventional farms in central India also found that organic wheat had higher zinc content than conventional wheat (Helfenstein et al., 2016). Plant-available soil zinc and wheat yields did not differ between conventional and organic farms, but the organic wheat averaged 20% higher zinc content. The organic wheat also contained higher concentrations of sulfur, despite soils on the organic farms having lower soil sulfur content. The researchers attributed these differences to the influence of soil biology. Healthier soil on the organic farms translated into more zinc in harvested grain.

The constellation of factors that affect crop growth and health make well-controlled, long-term studies of phytochemical levels in organic and conventionally grown crops rare. A notable exception was a ten-year study that documented mean levels of quercetin and kaempferol, two phytochemicals known to benefit human health, They were 79 and 97% higher, respectively, in the organically grown tomatoes (Mitchell et al., 2007). While flavonoid levels in the organically grown tomatoes increased over time as the organic matter content of the soil increased, the flavonoid content of the conventional tomatoes stayed relatively constant over the decade-long study. In other words, as soil health improved so did the tomatoes.

Increased soil organic matter generally makes micronutrients more plant available (Shuman, 1997). A 2018 study of farms in Ethiopia found that along with yields, the protein and zinc content of wheat grains more closely tracked levels of soil organic matter than mineral fertilizer applications (Wood and Baudron, 2018). Soil organic matter was the strongest predictor for zinc content in wheat, leading the researchers to conclude that increasing soil organic matter could increase crop nutrient content enough to improve human health (Wood and Baudron, 2018). Along these lines a study of zinc levels in wheat grown in central India found that organic wheat that produced comparable yields had almost 20% more zinc than conventionally grown wheat (Helfenstein et al., 2016).

## Other Studies

Several studies have addressed how farming practices influence concentrations of dietary antioxidants and other phytochemicals in food crops. For example, a review in the *European Journal of Nutrition* found agronomic practices could increase the content of beneficial phytochemicals ten-fold in broccoli and cauliflower, and double them in radishes (Schreiner, 2005). A study that assessed levels of vitamin C and total phenolics in strawberries, marionberries, and corn that had been grown by conventional vs. "sustainable" and organic practices, comparing the same variety of each crop grown on fields of the same farm in Corvallis, Oregon that were harvested at the same time and then immediately quick-frozen found that vitamin C and total phenolic levels in the sustainably-grown strawberries were about 20% higher than in conventional strawberries (Asami et al., 2003). Both the organic and sustainably-grown marionberries and corn had a total phenolic content more than 50% higher than conventionally-grown ones.

Studies of organic vs. conventionally grown tomatoes and tomato juice also found that organic varieties had significantly higher levels of polyphenols associated with lower risk of cardiovascular disease and certain types of cancer (Vallverdú-Queralt et al., 2012). Similarly, a French study found that organically grown tomatoes had higher vitamin C, carotenoid, and polyphenol levels (Caris-Veyrat et al., 2004). And an Australian comparison of wheat grown under organic and conventional management found no difference in most macronutrients, but more copper and a third more to half more zinc in organic wheat (Ryan et al., 2004). Notably, zinc levels tracked with colonization by mycorrhizal fungi, which conventional farming practices depressed.

Organic management and fertilization practices have been found to increase total phenolics in eggplant, pears, peaches, corn, apples, marionberries, and blueberries (Asami et al., 2003; Wang S. Y. et al., 2008; Reeve et al., 2016). Studies have shown that while fertilizing with sulfur increases phytochemical abundance, nitrogen fertilizer does the opposite, and can decrease the amount of glucosinolates in broccoli by as much as 70% (Verkerk et al., 2009). And an extensive Brazilian study found organic cultivation delivered higher total phenol and flavonoid content for a wide range of plant peels, leaves, and stalks (Lima et al., 2008). Specifically, the comparison looked at the peels of zucchini squash, bananas, potatoes, eggplant, oranges, limes, mango, passion fruit and radish, at the leaves of zucchini squash, broccoli, carrot, collard, cassava, radish and grapes, and at the stalks of broccoli, collard, and spinach. In other words, organic practices systematically increase the phytochemical content of a wide range of crops.

But the effect depends on the cultivar. A study of potato cultivation in Italy found that for certain varieties organic farming practices resulted in more phenolics, less nitrate, and better taste (Lombardo et al., 2012). A similar Spanish study found that certain Japanese plum cultivars grown using organic practices had significantly higher polyphenol and anthocyanin concentrations and greater total antioxidant capacity than conventionally raised plums (Cuevas et al., 2015). Notably, different cultivars had the highest values of different phytochemicals for each cropping system. So the specific crop varieties grown in comparative studies of different farming systems affect the size of any observed growing practice-based differences.

Controlling for such differences, Japanese researchers compared flavonoid content along with the anti-oxidative and anti-mutagenic properties of Chinese cabbage, spinach, Welsh onion, green peppers, and qing-gen-cai harvested on the same day from adjacent organic and conventional farms (Ren et al., 2001). The organic vegetables had 20–120% higher antioxidant activity and better suppressed mutation in cell cultures. In addition, flavonoid contents were higher in organic than in conventional vegetables, with quercetin levels up to ten times higher.

The Rodale Institute's farm systems trial is a notable long-term study of the effects of farming practices on the nutritional quality of food (Hepperly et al., 2018). Since 1981 the institute has grown the same crops in side-by-side plots in an ongoing field-scale comparison of organic and conventional practices. By 2003, soil organic matter and nitrogen levels had significantly increased on the organic plots, but not on the conventional plots. On average, oats from the organic system had roughly a third higher mineral content, ranging from 7% more potassium to 74% more boron, with 23% more iron and 40% more zinc. Vegetables grown under the two systems in 2005 also had large differences in total antioxidant and vitamin C levels. Organically grown tomatoes and jalapeno peppers, respectively, had 36 and 18% more vitamin C. Organic carrots had 29% higher total antioxidant levels. A little over a decade into this experiment the conventionally managed plots had lower biological activity than the cover cropped organic soils, which had increased in carbon over the course of the field trials (Wander et al., 1994). In other words, healthier soils with more soil life were producing more nutrient-dense crops.

A 6-year Colorado State University study comparing the influence of inorganic nitrogen fertilizers and manure on soil health, crop productivity, and crop quality in a continuous maize production system found no difference in crop yield but that manure increased soil health, soil mineral availability, nutrient uptake, and thus grain quality (Miner et al., 2020). Similarly, a 5-year study of the effects of organic and chemical fertilizers in Pakistan found that compared to chemical fertilizers, organic and integrated fertilization enhanced plant growth and yields, and that organic fertilizers increased aspects of soil health (carbon content and micronutrient availability) and phytochemical content (Noor et al., 2020).

## DISCUSSION

What's the dietary upshot from all these studies? Conventionally grown food adds more of the elements we add as fertilizer and two things undesirable in food—pesticides and heavy metals. And while there appears to be little evidence for differences in macronutrients between conventional and organic farming, studies dating back decades report significant differences in micronutrients (vitamins and minerals). But the most striking, human health-relevant result of previous studies is that they consistently find significantly more phytochemicals in organic foods, a result usually overlooked as they are not considered nutrients despite their known connections to human health.

Hence, it appears that much of the confusion and perennial controversy around whether farming practices affect the nutritional value of food stems from examining different aspects of a crop's nutritional profile of macronutrients, micronutrients, or phytochemicals. While nutritionists generally do not consider phytochemicals nutrients *per se* as they have no caloric value, many of these compounds have demonstrated connections to maintaining good health and preventing chronic diseases (e.g., Weisberger, 1991; Alloway, 2009; Kang et al., 2011; Wang et al., 2011, 2014; Del Rio et al., 2013; Zanotti et al., 2015). And because farming practices affect the levels of various phytochemicals in crops, the interpretation of whether farming practices affect the nutritional quality of foods appears to depend on how one defines nutrients.

Most agronomic comparisons, however, tend to focus on yields rather than nutritional quality, and studies have found that the effects of farming practices that enhance soil health can also increase yields. For example, a 2014 global review found that healthy earthworm populations boost crop yields by an average of 25 percent, enough of an increase to close the often-cited yield gap between organic and conventional farming (Van Groenigen et al., 2014). And while a 1990 study found that organic yields averaged almost 10% lower than conventional yields based on 205 comparisons of crop yields from prior studies that reported comparative observations and long-term replicated field trials across 26 crops, in half of the 30 direct yield comparisons organic crop yields equaled or exceeded conventional yields (Stanhill, 1990). Despite the average yield gap framing most discussions surrounding this issue, of the long-term field experiments surveyed in this review only half of the comparisons found statistically significant differences between organic and conventional yields, and a quarter of the harvests analyzed showed organic crops to out produce conventional ones (Stanhill, 1990). In other words, the yield gap was not consistent.

These studies raise the question of how much of a role improved soil health could play in closing the yield gap. A subsequent meta-study comparing yields of organic and conventional farming systems found that while organic yields were roughly 20% lower overall, diversified organic crop rotations reduced the yield gap to under 10% (Ponisio et al., 2015). The authors concluded that research investments in organic cropping systems could potentially eliminate the yield gap altogether. A recent review noted that yield differences between organic and conventional systems declined enough over time to significantly reduce or eliminate the yield gap after just several years of organic production (Fess and Benedito, 2018). This result highlights that a key, under-appreciated factor in many meta-studies comparing crop yields is inclusion of organic farms that were previously cropped for decades using conventional practices that depleted soil organic matter—and thus degraded soil health. As crop varieties bred for conventional farming systems produce low yields when grown in organic-matter-poor soils without synthetic fertilizers, breeding for performance in soil-health building farming systems presents substantial opportunities to enhance both nutrient density and yields.

## Relevance to Human Health

Soil biodiversity provides a range of benefits to human health through suppressing pathogens, and enhancing crop nutrient uptake and thereby the nutritional value of food (Wall et al., 2015). Numerous studies find that farming practices that affect soil life influence mineral uptake and phytochemical production, and the most consistent finding of studies that compare organic and conventional practices are significant differences in phytochemical production. Not conventionally classified as nutrients, phytochemicals are not necessary for growth or survival, yet numerous studies have linked dietary intake of various phytochemicals to human health.

Differences in the phytochemical content of foods are relevant to preventing inflammation and reducing risk of chronic diseases (Craig, 1997; Liu, 2003; Zhang et al., 2015). Certain phytochemicals boost human anti-inflammatory defenses and make malignant cells vulnerable to immune-system attack (e.g., Rao and Agarwal, 1999; D'Incalci et al., 2005). Medical researchers attribute the cancer-suppressing effects of consuming more fruits and vegetables to the antioxidant and anti-inflammatory phytochemicals that these foods contain (Murthy et al., 2009). Although not considered nutrients, phytochemicals help lower risk of chronic disease.

Several studies have investigated whether dietary differences impact human health. For example, a study of Swedish children found significantly higher risk of allergic conditions among those from public schools than for those at nearby Steiner schools catering to families that emphasized a biodynamic, vegetable-rich organic diet (Alm, 1999). Another comparison, involving almost 15,000 European children, found those from public schools who ate more conventional diets had higher incidences of asthma and food allergies (Alfven et al., 2006). A pair of Danish studies reported sperm counts were highest among men who consumed the most organic produce and lowest among those who consumed only conventional produce (Jensen et al., 1996; Juhler et al., 1999).

Another Danish study, a dietary intervention employing a double-blind, randomized, crossover design—the gold standard in medical trials—fed volunteers a prescribed diet of either conventional or organic foods and monitored their intake and excretion of five flavonoids (Grinder-Pedersen et al., 2003). Subjects ate either a conventional or organic diet with identical quantities of the same foods for 22 days, and then switched diets and repeated the process. When consuming an organic diet study subjects displayed increased antioxidant activity and had significantly higher levels of the flavonoids quercetin and kaempferol in their urine (Grinder-Pedersen et al., 2003).

Most recently, a study that tracked medical records over an average of almost 5 years for about seventy thousand French adults stratified participants according to their consumption of organic fruits and vegetables, meat, dairy, and eggs, tea, wine, vegetable oils, and cereals (Baudry et al., 2018). Those who reported higher organic food consumption also reported higher intake of fruits and vegetables, and lower intake of processed meat, poultry, and dairy products. Those consuming the most organic food had roughly a quarter to a third lower risk of cancer than those consuming the least (Baudry et al., 2018). But as higher organic food consumption was also associated with other factors, including income, education, and exercise, the differential health outcomes could also reflect health-related lifestyle factors other than diet.

Considered all together the mechanistic and comparative studies reviewed above indicate the need to focus on how farming practices—both conventional and organic—affect soil health, as soil life affects mineral micronutrient uptake and phytochemical production in crops. While few studies have addressed this link directly, many have pointed to mechanisms that help connect the dots and comparisons consistent with an influence of soil health on crop nutrient density.

## CONCLUSIONS

Although early studies pointed to contrasting effects of soil organic matter and chemical fertilizers on soil life in influencing the composition of crops, understanding why lay beyond the scope of conventional thinking. In subsequent decades, studies demonstrated mechanisms underlying connections that help explain, and potentially point to ways to reverse, reported historical declines in micronutrient density (Mayer, 1997; Davis et al., 2004; Ekholm et al., 2007; Davis, 2009). While there appears to be little evidence of significant differences in macronutrient composition, other than some conventional crops containing higher protein levels, there is substantial evidence that farming systems impact micronutrient levels. And the two most compelling findings of previous studies are that conventional crops consistently have higher pesticide levels and organic crops have higher phytochemical levels, particularly antioxidants and anti-inflammatory compounds.

The evidence and mechanisms discussed above support concluding that there are significant differences in the phytochemical content of organic and conventional crops—especially in compounds that contribute to good health but that are not essential for life. Moreover, the role of soil life in influencing the micronutrient and phytochemical content of crops indicates that both the organic vs. conventional distinction and standard definitions of what constitutes a nutrient are inadequate for fully assessing the dietary impact of farming practices on human health. While the simplest way to consume more phytochemicals is to eat more fruits and vegetables—however they are grown—studies consistently show that organic and regenerative crops contain higher levels than conventional crops, and often several times more.

All this points to the need to reframe nutritional and agricultural research and policy around the effects of farming practices on soil health, as simply basing comparisons on the organic vs. conventional distinction can blur underlying differences due to the effects of farming systems on soil life. Further research evaluating the role of soil health on the nutrient-density of food is needed to enhance our understanding of the linkages between diet, farming practices, and human health.

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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