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Exploring the Relationship Between Soil Health and Food Nutritional Quality:

A Summary of Research Literature

2022

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Executive Summary

Introduction and Approach
Many on-farm and environmental benefits associated with improving soil health are well established, but the relationship between soil health and human health through food nutritional quality remains largely unknown. To investigate this relationship, peer-reviewed literature was searched and analyzed with the objective of evaluating the potential link between soil health and food nutritional quality. Four criteria were used in selecting literature for evaluating soil health and food nutritive quality relationships. Namely, each study was evaluated for providing:

- comparisons of crop and soil properties under different land management practices or cropping systems;
- measurement of soil health related parameters under different management practices or systems;
- measurement of crop nutritive characteristics; and
- measurement of outcomes relevant to human health (or, at minimum, consideration of human health outcomes in interpreting the data).

Findings
Initial searches for literature produced as many as 1,000 results, but few papers contained enough relevant information for addressing the objective of this evaluation. Subsequent searches were then conducted using keywords for specific soil health management practices in combination with terms related to crop nutritive outcomes. This yielded more relevant papers, as did including specific crop terms. After an initial survey of a broad assortment of crops, the review was narrowed to examining published evidence connecting soil health and crop characteristics for tomato (*Lycopersicon esculentum* Mill.) and wheat (*Triticum aestivum* L.) due to their nutritional, economic, and agronomic importance in North American agriculture and similar agricultural systems.

Focusing initial searches with keywords relevant to soil health-promoting agronomic management practices and keywords specific for crop nutrition or nutritive value yielded 72 papers that offered enough information to be useful. Of these, 37 focused on row crops (e.g., corn, wheat, soybean) alone or in rotation with one other. The remainder were publications on tomato, rice, potato, butternut squash, bean, chickpea, broccoli, cassava, or berries. Publications demonstrating causal links between soil health and crop nutritive changes were rare, with most limited to documenting the effect of land management on crop quality and only hypothesizing that soil parameters influenced nutritive differences. Possible causal mechanisms linking soil health-promoting management practices and crop nutritive value included:

- changes in microbial diversity,
- changes in nutrient cycling,
- effects on arbuscular mycorrhizal fungi and other fungi that colonize crop plant roots and affect nutrient uptake,
- plant response to environmental stressors associated with land management practices,
- presence of perennial plants or a leguminous crop in annual cropping systems, and
- changes in soil physical and chemical properties affecting crop water and nutrient uptake.

Sixteen papers compared nutritional outcomes in organic and conventional production systems. Of these, only a few reported soil measurements. A paper describing a meta-analysis of 74 studies comparing organic and non-organic farming systems concluded that soils in organic farming systems had significantly higher levels of soil organic carbon (SOC), greater carbon stocks, and greater carbon sequestration rates than conventional systems. In general, principles relating SOC with mineral nutrient availability in soil support a mechanism linking SOC with crop nutritive value. However, differences in nutritional composition of organic crops could not be attributed to changes in soil health because most of these publications lacked key soil health and crop nutrient measurements.

WHEAT GRAIN PROTEIN CONCENTRATION WAS OFTEN INCREASED BY INCLUDING A LEGUME CROP IN ROTATION

Wheat

There is considerable interest in the effect of tillage intensity and crop rotation on grain quality and yield. The influence of tillage intensity on grain protein concentration or content (concentration x harvested mass) was inconsistent among rotations, among years within individual experiments, and among publications. In contrast, wheat grain protein concentration was often increased by including a legume crop in rotation, even though different experiments included different crop rotation combinations and durations. In many cases, rotation with a legume resulted in increased protein content and yield, likely related to N availability from legume crop residues. Increased soil organic matter and soil total N in some rotations may have promoted root growth, which in turn increased water and nutrient uptake. Diversifying continuous monocrop wheat systems or replacing fallow with another crop, commonly a legume, increased grain Zn concentration in multiple studies. A significant increase in grain Zn occurred in rotations with perennial crops, e.g., alfalfa-hay, possibly related to higher soil organic matter and an associated increase in cation exchange capacity, or presence and function of arbuscular mycorrhizal fungi. The effect of crop rotation on the concentrations of other macro- and micronutrients (K, Ca, S, Mg, P, Fe, Mn and Cu) was inconsistent across studies.

Tomato

Most of the 12 publications that compared effects of agronomic management systems on tomato nutrient composition focused on comparing outcomes of organic and conventional production practices. Most studies lacked key data for assessing relationships between production practices and crop nutritive value, e.g., data on mineral nutrient concentrations in both soil and fruit, or yield data for calculating crop nutrient content. In some papers, but not all, organic production systems resulted in significantly different concentrations of macro- and micronutrients in tomato fruit, compared to conventional systems. However, apparent treatment-related changes described in some studies (e.g., changes in mineral concentration in association with yield change) were not observed in others. Similarly, organic production practices led to increased concentrations of lycopene and β-carotene in fruits in some experiments, but not others.

A GENETIC COMPONENT TO TOMATO CROP RESPONSE TO MANAGEMENT ALSO APPEARED TO INFLUENCE RESULTS

In addition, a genetic component to tomato crop response to management also appeared to influence results. For example, one tomato cultivar exhibited a significantly higher ascorbic acid concentration under organic production than under conventional practices; however, the same observation was not made for a different tomato cultivar. Source of N in fertilizer (organic or synthetic) had no effect on concentrations of phenolic compounds that are important antioxidants, nor in chemical activities of soluble antioxidants. It seems plausible that when management practices on tomato nutritive quality were observed, they could be linked to different levels of nutrient availability and cation exchange capacity in soils managed organically compared to conventionally. However, the many different management practices applied and their highly diverse and individual impacts on soil physical, chemical, and biological characteristics, render data from organic vs. conventional systems highly confounded. Thus, comparisons and conclusions about the effects of organic vs. conventional management systems were difficult to discern.

Conclusions and Recommendations
Although both wheat and tomato are widely produced and consumed crops, only a small number of publications included data appropriate for evaluating soil health with crop nutritive quality. This finding reflects the lack of attention that has been given to investigating the relationships between soil health and food nutritional quality.

Determining causal mechanisms among soil health management systems, soil health outcomes, crop nutrition, crop nutritive value, and human health requires research that must include specific, carefully selected, and highly controlled or characterized aspects of soil, crop, and human nutrition-relevant variables. To address these issues, we recommend future research studies be conducted that include:

- well defined, consistently applied soil health-promoting management practices,
- relevant and methodologically consistent soil health measurements,
- methodologically consistent measurements of general soil conditions (physical conditions, mineral nutrient concentrations, etc.),
- methodologically consistent crop nutrient measurements (concentrations of mineral nutrients, plant secondary compounds, proteins, and others in consumed plant tissues relevant to human health),
- crop yield measurements,
- methodologically consistent indicators or measurements of human health attributable to nutrition, and
- a diversity of crops that reflects the human diet globally.

Experiments, measurements, and methods should be selected specifically to enable translation of results into meaningful implications for human health. This must be achieved by interdisciplinary research teams, including human nutrition experts, to interpret connections between agronomic data and dietary impact. Understanding the connections among soil health, crop nutrient concentrations/content, and human health is essential to guide future land management policies and practices, as well as to address consumer demand. Such additional research is justified to meet global sustainability, nutritional, and food-security goals.

Abstract

Many on-farm and environmental benefits associated with improving soil health (SH) are well established, but unknowns remain regarding the relationship between soil health and human health through food nutritional quality. To investigate this relationship, peer-reviewed literature was searched for publications that addressed four criteria useful for evaluating soil health and food nutritional quality: SH promoting management practices, SH measurements, crop nutritive outcome measurements, and related implications for human nutrition and health. Publications on wheat and tomato were chosen for in-depth consideration based on their globally significant dietary contributions. Only a small number of studies contained information sufficient for such an analysis, and they were inconsistent in conclusions. Thus, much additional research is needed to clarify this topic. Valuable research would include: 1) studies designed to collect data to satisfy the four criteria listed above; 2) collection of data based on standardized soil health and food nutritional quality measurements; 3) examination of a wide range of foods, especially staple crops that are important in human diets worldwide; 4) representation of diverse farm scales and management systems; and 5) focus on both nutrient concentration and total content.

I. Introduction:

There are many reasons to advocate for land management practices that prioritize soil health (SH), defined by the United States Department of Agriculture, Natural Resources Conservation Service (USDA, NRCS) (2018) as "the continued capacity of a soil to function as a vital, living ecosystem that sustains plants, animals, and humans." Management practices affect SH and many soil properties that support crop health, including the availability of mineral nutrients and water that affect crop yield and quality. Land management practices considered effective in improving SH include are designated by the NRCS as Soil Health Management systems and include conservation crop rotations, cover crops, no-till (NT), mulch tillage, mulching, and nutrient management (USDA, NRCS, 2017). These practices build soil organic matter (SOM), which may increase farm-level biodiversity and reduce the need for chemical inputs. Popular understanding holds that such changes in the production system, along with other physical, chemical, and biological changes associated with increased SOM, can improve the taste and nutritive qualities of crops when compared to crops produced in conventional farming systems.

Important connections between SH and human health have been implied in terms of the influence of SH on soil pollution and toxicity, soil microbiology, and pathogens (Brevik et al., 2020). However, most research connecting soil properties and human or animal nutrition relies on identifying and ameliorating nutrient deficiencies in the soil for particular crops in particular geographic regions (Fischer et al., 2020). Less research is available on the interacting effects of soil properties and land management practices on nutrient concentrations in the harvested component of the crops. Even less attention has been devoted to determining whether SH promoting management practices lead to changes in crop nutrient composition. Studies to determine whether any such improvements in SH confer biologically significant, measurable benefits to human or animal health remain rare indeed. To date, no consensus has been possible.

In 2018, the Soil Health Institute held a multi-disciplinary Conference on Connections Between Soil Health and Human Health to bring scientific communities together, establish the current state of our collective knowledge, identify gaps and associated priorities, and determine a path forward. Nearly 200 participants from academia, industry, government, and the non-profit sector discussed subjects ranging from the microbiome on farmland to urban soil contamination, all with an eye on public health. Of the ten recommendations offered by conference participants, five addressed the need to explore connections between SH and the nutritional content of food.

To assess the state of knowledge relating SH promoting practices to crop nutritive value and human health outcomes, we identified and evaluated peer-reviewed literature as a first step in determining relationships connecting SH promoting management practices, measured SH outcomes, resulting crop nutritive properties (nutrient concentration and total quantity), and measurements of human health outcomes.

II. Methods

Web of Science provided the database for this review of literature focused on crops grown for direct human consumption. For a publication to be considered as demonstrating a connection of SH or SH promoting practices to human health, four criteria were deemed ideal:

- comparison of crop and soil properties under different land management practices or cropping systems;
- measurement of SH related parameters under the different practices or systems;
- measurement of crop nutritive characteristics; and
- measurement of outcomes relevant to human health (or, at minimum, consideration of human health outcomes in interpreting the data).

An initial literature search was based on phrases directly linking SH to crop nutrient outcomes. Search terms included phrases related to SH, (e.g., “soil health”, “soil organic matter”, “soil carbon”), in combination with terms related to crop nutritive outcomes (e.g., “crop nutrients”, “crop nutrient uptake”, “plant nutrient uptake”, “crop nutrient content”, “food quality”, “crop quality”). Some of these searches produced as many as 1,000 results, but few papers contained enough relevant information to make them important to a review of this topic. Another search was based on terms identifying specific SH management practices (e.g., “tillage”, “cover crop”) in combination with the previously used terms related to crop nutritive outcomes. This yielded more relevant papers, as did including specific crop terms to these searches.

After an initial survey of a broad assortment of crops, the review was narrowed to tomato (*Lycopersicon esculentum* Mill.) and wheat (*Triticum aestivum* L.), two nutritionally, agronomically and economically important crops in North American agriculture and similar industrial agricultural systems, as example crops for examining published evidence connecting SH and crop characteristics.

III. Results of Initial Survey of Literature on Row- and Horticultural Crops

Once specific crop names were included in searches, the number of publications identified initially was proportional to the total number available for the different crops. For example, combining the search term “soil organic matter” with “corn nutrient content” returned 236 publications, whereas “soil organic matter” with “cassava nutrient content” returned only 20.

The number of papers with relevance to crop nutritive value and human health was very limited. Many papers focused on the effect of land management practices (e.g., reduced tillage intensity, crop rotation, cover cropping, mulch retention), on crop yield. Data on changes in soil parameters (e.g., soil carbon (C) and nitrogen (N) fractions, bulk density, pH), and crop quality parameters (e.g., protein concentrations, macro- and micronutrients) were often included in these reports. Other papers compared nutrient concentration or content outcomes from different land management systems but did not include measurements of the effect of these practices on SH parameters (Chen et al., 2012; Gooding et al., 2007; Houx III et al., 2014, 2016; Park et al., 2015). In these cases, the effect of such practices on SH can only be assumed; similarly, causal mechanisms driving changes observed in crop nutrient composition relative to changes in soil parameters are unproven. In the case of corn, soybean, wheat, and rice grain, the most commonly measured nutritive components were nitrogen (N), phosphorous (P), potassium (K), and zinc (Zn); data on iron (Fe), copper (Cu), calcium (Ca), magnesium (Mg), manganese (Mn), selenium (Se) and sulfur (S) were presented in fewer publications. Only two publications reported on plant secondary compounds (PSCs), including data on changes in wheat grain phenol concentration (Park et al., 2015; Zuchowski et al., 2011). Data or discussion in these papers to establish relevance of these measurements to crop nutritive value and human health was very limited for all crops.

In all, initial searches across multiple crops yielded 72 papers to include in this review of SH related practices on measurements on crop nutritive outcomes. Most of these papers did not meet all four ideal criteria because almost all lacked information on the nutritional implications for human health, and more than half lacked actual data on soil parameters. Given the data that were presented, however, these 72 papers offered some insights into the effects of agronomic practices and related environmental conditions on crop characteristics that could be related to nutritional quality or quantity, and at least hypothetical outcomes for human health.

Of the 72 papers, 37 focused on row crops (e.g., corn, wheat, soybean) alone or in rotation with each other. Much of the soybean and corn produced is used in livestock feed, making these results only indirectly applicable to human nutritional outcomes. Other crops among the 72 papers are rice (Huang et al., 2016; Ibrahim et al., 2011), potato (Davis, 2013; Ekeberg, 1996), butternut squash (Zinati, 2019), bean (Gooding et al., 2007), chickpea (Gunes et al., 2007), broccoli (Davis, 2013), cassava (Fischer et al., 2020) berries (Asami et al., 2003), and tomato (see below).

These papers represent diverse agronomic systems, locations, soil types, and climates, and offer different pathways for explaining relationships between SH management and crop nutritive outcomes. However, publications demonstrating causal links between SH and crop nutritive changes were rare. Good examples are the two papers (Wood et al., 2018; Fischer et al., 2020) that examined the effect of different amounts of SOM on crop nutritive outcomes on smallholder farms in Africa. Another (Miner et al., 2020) attempted to determine whether changes in SH impacted corn crop nutrient concentration in Colorado, USA. Unfortunately, most papers were limited to documenting the effect of land management practice on crop quality and used changes in soil parameters to offer hypotheses about potential nutritive differences. Several papers suggested that tillage intensity, crop rotation, and organic vs. synthetic fertilizer inputs could change nutrient cycling and availability in soil, representing a causal pathway from management practices to crop nutritive outcomes (Asami et al., 2003; Barański et al., 2014; Ekeberg, 1996; Fischer et al., 2020; Houx III et al., 2014). This seems plausible given the well documented relationship between available soil N and crop N concentration, as well as other links between soil management and soil chemical properties. On the other hand, in two papers, inherent differences in soil type and parent material appeared to have the largest effect on macro- and micronutrient levels in food (Watson et al., 2012; Wilkes et al., 2010).

Effects of management practices on soil physical properties offers another possible pathway to crop nutritive value and human health. Several papers provided data on changes in soil water holding capacity, bulk density, and root penetration in response to management practices (Aghili et al., 2014; Ibrahim et al., 2011; Riedell et al., 2009, 2013), although in some cases nutrient composition specifically in the edible portion of the plant was not measured (Colla et al., 2000; Lipiec & Stępniewski, 1995; Sainju et al., 2000, 2002).

Other papers provided a focus on effects of land management on soil biological properties, such as microbial biodiversity (Tautges et al., 2016), colonization of roots by arbuscular mycorrhizal fungi (AMF) and non-mycorrhizal fungi (non-MF) (Cavagnaro et al., 2006; Galvez et al., 2001; Lehmann et al., 2014; Mozafar et al., 2000; Pellegrino et al., 2015; Ryan et al., 2008), presence of perennials in annual cropping systems (Riedell et al., 2013; Smith et al., 2017; Turmel et al., 2009), crop-specific differences in effects of land management practices on nutritive outcomes (Adeli et al., 2017, 2019; Houx III et al., 2014, 2016), and nutrient concentrations in different edible plant parts (e.g., grains, tubers, fruit) (Fischer et al., 2020). Such publications illustrated the great biological complexity in soil, which raises interesting questions about causal links among management practices, soil biology, crop nutrient characteristics, and ultimate effects on human health. However, this complexity renders broad generalizations difficult to define.

Soil health is frequently of interest in research in organic farming systems. Some of the defining practices of organic farming systems follow the Principles for High Functioning Soils (NRCS, 2017), build soil organic carbon, and directly impact SH, making them relevant to mention here. Despite great interest currently in potential benefits of organic farming systems relative to conventional systems, demonstrating that such benefits could ultimately improve human health through crop nutritive value is fraught with confounding factors. This is not surprising given the myriad differences in the physical, chemical, and biological properties of soil resulting from organic versus conventional farming management. Sixteen papers compared nutritional outcomes in organic and conventional production systems. Of these, only a few reported soil measurements (Colla et al., 2000, 2002; Tautges et al., 2016). A meta-analysis of 74 studies comparing organic and non-organic farming systems concluded that soils in organic farming systems had significantly higher levels of soil organic carbon (SOC), greater carbon stocks, and greater carbon sequestration rates than conventional systems (Gattinger et al., 2012). Similarly, organically managed soils in long-term field plots had higher SOM levels than conventional NT systems (Teasdale et al., 2007). However, it is not possible to determine the differences in nutrient composition of organic crops attributable to changes in SH because most of these publications lacked SH related measurements. One exception relates to certain phytochemicals in horticultural crops that have implications for human health. A recent literature review (Reeve et al., 2016) and a meta-analysis based on 343 studies (Barański et al., 2014) comparing organic and conventional crops concluded that significantly higher concentrations of PSC, especially polyphenols, in organic systems may be the result of plant responses to changes in nutrient cycling, nutrient availability, or environmental stress in organic systems.

IV. Results: Tomato and wheat case studies

To facilitate analysis and compare results across studies, wheat and tomato were selected as two examples of how SH management practices and changes in soil physical, chemical, and biological properties may affect grain and fruit nutritive outcomes.

Wheat and tomato are grown widely for human food rather than for feed grain or other uses (e.g., corn for ethanol), represent significant acreage of production, and make significant contributions to diets in the U.S. and around the world. Worldwide, tomatoes are one of the most popular fruits (tomatoes contain seeds and thus are fruits, but their culinary uses lead many to consider them vegetables); annual global production is more than 159 million tons (Anton et al., 2014), whereas wheat is the third most grown cereal crop behind corn and rice, and is the crop contributing most calories to a large portion of the global population (Aghili et al., 2014). These two crops also represent very different contributions to the human diet, with wheat as an important dietary source of calories, carbohydrates, protein, and fiber, while tomatoes are rich in vitamins, minerals, and are a primary source of PSCs with antioxidant properties such as phenols, flavanols, carotenoids and ascorbic acid, among others (Mitchell et al., 2007). Wheat and tomatoes are produced under very different agronomic systems, allowing for a comparison of the effects of soil health management practices on crop nutritive outcomes, to the extent data will allow, and the possible pathways that connect SH to crop nutrient concentration or content.

Case Study 1: Wheat

Nineteen publications addressed the relationship between land management practices, SH measures, and wheat grain nutrient outcomes (Table 1). Reduced till and NT systems are increasingly prevalent in grain production systems to reduce input costs and labor while providing environmental benefits. Therefore, there is considerable interest in the effect of tillage intensity on grain quality and yield.

Wheat grain protein was often reported (14 of the 19 papers) when grain quality was measured in response to land management alternatives (Table 2). Greater grain protein concentration and content (a function of concentration and yield quantity) are relevant for human nutrition, especially in parts of the world where protein from non-animal sources is important for meeting dietary needs. Protein is also an indicator of grain quality influencing a crop's potential uses and profitability.

Long-term studies have resulted in conflicting results for effects of tillage type on wheat protein concentration and content. On dryland soil in Montana, no significant difference in grain protein removal was observed after 20 years of continuous wheat production (W-W) under conventional tillage (CT) or NT (Sainju et al., 2009). Yield was not reported, so grain protein content could not be calculated. Similarly, another 20-year study of wheat under NT vs CT on eroded soils in Mississippi also found no differences in grain yields and protein removal (Adeli et al., 2017). In contrast, after 18 years of CT or NT on three crop rotations (W-W, clover-W, bean-W), significantly lower protein concentration and content was found under NT than under CT in all rotations (Amato et al., 2013).

Results are also conflicting in shorter-term studies. Similar grain protein concentrations of 15.7 and 15.8% occurred under CT and NT, respectively, but a yield suppression caused a significantly lower grain protein removal with NT (Malhi and Lemke, 2007). Two other studies found significantly lower grain protein concentration in NT treatments after 6 years of CT or NT management (López-Bellido et al., 2001; Park et al., 2015). In contrast, protein concentration and content were inconsistent during years 6 through 8 of a long-term tillage experiment; this variation may have resulted from advantages of NT (soil water retention) during years with low rainfall (De Vita et al., 2007). Year to year variation also occurred in another study in which stratification of plant residues under NT may have affected plant nutrient availability, and thus yield and grain nutrient outcomes; while soil nitrate-N and ammonium-N were more stratified under NT, this did not have a limiting effect, and greater grain N removal occurred under NT in year 7 and similar grain N removal in year 8 (Lupwayi et al.,2006). One short-term study demonstrated the interaction of soil type with the effect of tillage on grain nutrient outcomes (Wilkes et al., 2010). Due to the short-term nature of this study, soil type had a larger effect on grain outcomes than tillage practices, repeating the previously mentioned significant effect of soil intrinsic properties on crop nutritive outcomes (Watson et al., 2012).

As with wheat grain protein, effects of tillage on concentrations of minerals in wheat grain were highly inconsistent. After 7 years of CT or NT management, significantly greater concentrations of P, Zn and K, a significantly lower concentration of Ca, and no significant differences in Fe or Cu concentration occurred in NT grain; wheat roots had significantly greater levels of non-MF colonization, which was related to nutrient uptake (Mozafar et al., 2000). In contrast, there was no significant effect of tillage treatments on grain P concentration (Lupwayi et al., 2006; Park et al., 2015); another reported lower P removal with NT (Adeli et al., 2017); and yet another (Park at al., 2015) reported lower grain concentrations of Ca, Fe, and Zn with NT, but no effect on Cu. In summary, no consistent effect of reduced tillage intensity on grain protein concentration or content can be concluded.

Two additional SH management practices in wheat production systems include fallow duration and crop rotation diversity. Either may affect grain nutritive outcomes (Table 2).

Replacing the fallow period in rotation (F-W) with either wheat or pea resulted in significant increases in soil total N (STN), particulate organic N, potential N mineralization, microbial biomass-N, and ammonium-N after 20 years and resulted in significantly greater grain protein removal (Sainju et al., 2009). Similarly, in a 12-year study, significantly higher grain protein concentration occurred when a F-W rotation was replaced with a lentil green manure-wheat (LGM-W) rotation (Zentner et al., 2004). LGM-W had greater yields than the F-W rotation on average, resulting in greater protein removal in the LGM system.

In contrast, protein concentration in grain was not different among W-W, Pea-W (P-W), lentil-wheat, or the typical F-W rotation in a short-term study (Chen et al., 2012); however, a significant increase in grain protein occurred when lentil grown for green manure replaced the fallow (Zentner et al., 2004). In a comparison of 3-year rotations among different sequences of wheat (W), peas (P), and canola (C), all rotations yielded significantly greater grain protein concentration and removal than continuous wheat (Gan et al., 2003); protein concentrations were the same among the C and P rotations (as in Hirzel et al., 2020)., However, when accounting for yield, P-P-W had significantly greater protein removal than C-C-W.

Effects of crop rotation varied with tillage type after 18 years of CT or NT management on three crop rotations. Under CT, bean-W and clover-W rotations had significantly greater grain protein concentrations than W-W, while under NT, crop rotation had no effect. However, greater wheat yields with clover-W and bean-W rotations, compared to W-W, were consistent across both tillage types, resulting in significantly greater grain protein removal per hectare in these rotations (Sainju et al., 2009).

Including perennial plants in diversified rotations has the ability to improve soil health further by minimizing soil disturbance and maximizing the presence of living roots (USDA, NRCS, 2018). Significant differences in grain nutritive outcomes occurred under annual and perennial rotation systems. Significant differences in grain nutrient concentrations occurred only when perennial alfalfa was included among 10 different rotations. Grain N, S, Mg and Zn concentrations were significantly greater in alfalfa rotations, while no significant changes occurred in grain concentrations of P, K, Ca, Cu, Fe or Mn in any rotation (Smith et al., 2017).

In a comparison of annual wheat production to a perennial forage-wheat rotation under either conventional or organic management, the organic-annual wheat combination produced grain with the lowest protein concentration. The other three treatment combinations produced grain with greater protein concentrations that were generally comparable (Turmel et al., 2009). However, grain protein removal in the organic perennial system was still far less than that produced under either conventional system due to yield suppressions. Other significant differences included lower grain P and Mn concentration in perennial rotations, lower S concentration in both organic systems, and increased Cu in the organic perennial rotation. Many of these results were inconsistent with those reported above (Smith et al., 2017).

In summary, wheat grain protein concentration was often increased by incorporating a legume crop in rotation; this appeared to be consistent even though rotation studies differed in rotation combinations and duration (Chen et al., 2012; Gan et al., 2003; Smith et al., 2017; Turmel et al., 2009; Zentner et al., 2004). In many cases, rotation with a legume crop resulted in increased protein content due to an associated yield increase (Amato et al., 2013; Chen et al., 2012; Gan et al., 2003; Hirzel et al., 2020; Sainju et al., 2009; Zentner et al., 2004). Diversifying continuous monocrop wheat systems or replacing fallow with rotation with another crop, commonly a legume, increased grain Zn concentration across studies (Ryan et al., 2008; Smith et al., 2017; Soltani et al., 2014; Turmel et al., 2009). A significant increase of grain Zn occurred in rotations with perennial crops, e.g., alfalfa-hay (Smith et al., 2017; Turmel et al., 2009). The effect of crop rotation on the concentration of other macro- and micronutrients including K, Ca, S, Mg, P, Fe, Mn and Cu was inconsistent across studies, and no significant trends occurred (Hirzel et al., 2020; Ryan et al., 2008; Smith et al., 2017; Turmel et al., 2009).

Possible mechanisms connecting soil health and wheat nutritive outcomes:
Research relating SH and wheat nutritive value offers many possible pathways between management practice and grain nutrient outcomes. In several papers already cited, SOM and specific organic N and C fractions increased under NT compared to CT (De Vita et al., 2007; Malhi & Lemke, 2007; Sainju et al., 2009) and with diverse crop rotations replacing fallow periods or continuous wheat crops (Sainju et al., 2009; Smith et al., 2015; Soltani et al., 2014; Turmel et al., 2009). In some cases, systems with increased soil organic N or soil total N also exhibited increased grain N concentration (Turmel et al., 2009; Wood et al., 2018) and content (Sainju et al., 2009). However, increases in soil organic N did not always result in increased grain N concentration (Adeli et al., 2017; Amato et al., 2013; Malhi & Lemke, 2007; Park et al., 2015) and content (Turmel et al., 2009). Greater grain protein concentration in CT wheat (compared to NT) may occur because soil cultivation can increase N mineralization by altering soil structure, soil temperature, and the distribution of crop residues along soil profile, thus increasing soil NO3-N content and grain N (Amato et al., 2013; López-Bellido et al., 2001; Park et al., 2015). A diverse crop rotation may have increased soil NO3-N because stubble from previous N-fixing leguminous crops was incorporated into the soil, leading to greater grain N in these systems (Gan et al., 2003). Similarly, increased grain protein content appeared to be a consequence of the contribution of residues from a preceding legume cover crop that was mineralized (Hirzel et al., 2020).

Increased SOM and soil total N may have promoted root biomass, which in turn increased water and nutrient uptake (De Vita et al., 2007; Sainju et al., 2009). Increased water holding capacity with NT systems may have led to increased yield and, in some cases, protein removal (Amato et al., 2013; De Vita et al., 2007). However, lower grain protein concentration with NT may be explained in part by abundant water uptake and thus greater kernel weight and volume (Park et al., 2015).

Six papers indicated apparent effects of cropping system practices on Zn in wheat (Table 3). A relationship between SOM, soil total N, and Zn uptake was suggested in multiple studies, where soil N and amino acids from decomposing N-rich cover crops apparently stimulated the synthesis of Zn chelating compounds, enhancing Zn uptake and transport throughout the plant (Aghili et al., 2014; Rana et al., 2012; Soltani et al., 2014). Another possible mechanism may be related to the outcome of management practices that promote SH through increases in SOM, which in turn increases soil cation exchange capacity; Zn (which commonly occurs as a cation in soil) may be better retained in soil and exchanged with plant roots in soil having increased SOM (Wood et al., 2018). However, increased SOM can also tie up Zn cations, making them less available to the plant (Smith et al., 2007).

Colonization by roots of AMF may also affect concentration of Zn in wheat grains. The extent of AMF and non-MF colonization is not one of the indicators of SH as defined by the Soil Health Institute's North American Project to Evaluate Soil Health Measurements (Norris et al., 2020). However, some of the same management practices that promote SH also promote establishment and diversity of AMF in soil and colonization of roots. Such practices include diverse crop rotation, increased presence of living roots, and reduced soil disturbance (Pellegrino et al., 2015). Increased grain Zn concentrations were associated with crop rotations that increased colonization of wheat roots by AMF and non-MF. Replacing fallow with a non-host crop, like canola, did not have the same effect (Mozafar et al., 2000; Ryan et al., 2008). Compared to a fallow-wheat rotation, a rotation in which wheat was preceded with linola or clover led to significantly greater levels of AMF colonization in roots, greater Zn concentration in grain, and greater Zn removal; replacing the fallow with canola, a non-host of AMF, did not have these benefits (Ryan et al., 2008). Furthermore, in this same study, the ratio of phytic acid to Zn in soil was inversely related to AMF colonization, suggesting that as AMF colonization increased, Zn became more bioavailable. A meta-analysis (Pellegrino et al., 2015) also found strong, significant correlations among AMF colonization, grain yield, and P concentration; a moderate, positive relationship was found for AMF colonization and Zn concentration.

Table 1. Summary of published research on the effect of cropping system management on soil parameters and grain nutritive component outcomes

Location	# Years	Soil	Cultivar	Cropping system°		Soil parameters measured✦	Grain components measured❖	Reference
				Base management	Comparison management			
Alberta, Canada	7-8	Dark Gray Luvisol, sandy loam	*Triticum aestivum*	CT	NT	+ NH_3-N, + K, - P at 5-20cm, = NH4-N, = P at 0-5cm,	+ N in first year, = K, = P, = N in second year	Lupwayi et al. (2006)
Saskatchewan, Canada	8	Gray Luvisol (Boralf), sandy clay loam	*Triticum aestivum L.*	CT, NR	NT, R	+ LFC, + LFN, = SOC, = TON	− N with NT, + N with R, − C with NT, + C with R	Malhi et al. (2007)
Mississippi, USA	20	Alifsol, Loring silt loam	Winter wheat cv. Pioneer 26R87	CT C-W, No-CL	NT C-W, CL	+ pH with CL at 0-15cm, + STN with CL at 0-15cm , + Total C with CL, + K, + Ca, + Mg, + P, + Zn at 0-15cm, + Bulk density with NT, + WSA with CL, + MBC	+ N with CL, + P with CL, + K with CL, − P with NT, − K with NT, = N with NT	Adeli et al. (2017)
Oregon, USA	5-6	mesic Typic Haploxeroll, Walla Walla silt loam	Soft white winter wheat, ORCF 102	CT	NT	--	− Protein, − Mg, − Ca, − Fe, − Zn, − Cu, + Mn, − Total Phenols, = P	Park et al. (2015)
Foggia, Italy	6-8	Typic Chromoxerert, clay loam	*Triticum durum, Desf.*	CT	NT	+ SOC at 0-30cm, − SOC at 30-60cm , + STN, + Bulk density, + WHC	− Protein	De Vita et al. (2007)
Sicily, Italy	18	Chromic Haploxerert	*Triticum durum, Desf.*	CT W-W, CT W-Clov, CT W-B	NT W-W, NT W-Clov , NT W-B	--	− Protein with NT, − Protein RT W-Clov, + Protein CT W-B and W-Clov, = Protein RT W-B	Amato et al. (2013)
Zurich, Switzerland	7	Dystric Gleysol	*Triticum aestivum L.*	CT	RT, NT	+ AMF and non-MF, + P at 0-5cm, = P at 5-30cm, pH, SOC	+ P, + K, + Mn, + Zn, − Ca, = Fe, = Cu	Mozafar et al. (2000)
New South Wales, Australia	1	Grey Vertisol (GV) and Red Kandosol (RK)	*Triticum aestivum L.*	CT	NT	--	− N on V soil, + N on K soil	Wilkes et al. (2010)
Córdoba, Spain	6	Vertisol (Typic Haploxererts)	*Triticum aestivum L.*	CT, W-W	NT, F-W, Sun-W, B-W, CP-W	--	− N with NT and Sun-W, + N with B-W, CP-W, F-W	López-Bellido et al. (2001)
Montana, USA	21	Kandosol	*Triticum aestivum L.*	CT F-W	CT W-W, CT W-P, RT W-W, NT W-W	+ STN, + PON, + PNM at 0-20cm, + MBN, + NH4-N at 0-20cm with CT W-P, = NH_4-N at 0-5 cm and 5-20, = PNM at 0-5cm, = NO_3-N at 0-5cm, = Bulk density, +/− NO_3-N but greatest in CT W-P	+ N	Sainju et al. (2008)
Alberta, Canada	>15	Orthic Dark Brown Chernozems, loam	*Triticum aestivum L.*	W-W	F-W, F-W-W, OP_{LM}-W-W, F_{LM}-W-W, GM-W-W, F-W-W-A-A-A	− SOC with F in rotation, + SOC with LM and GM additions, − LFN with F in rotation, = LFC	+ N with A-W and F-W, + Zn with A-W and W-W, Highest N, Zn, Cu, Mn, Mg, S with W-A rotation	Smith et al. (2018), Smith et al. (2015)
Manitoba, Canada	10	Rego Black Chernozem	*Triticum aestivum*	Con-ANN	Org-ANN, Con-PER, Org-PER	+ N with PER at 0-15cm, − N with Org-ANN at 0-15cm, − P at 0-15cm, − S, = N at 15-60cm, = K	− N with Org, − P with Org-PER and Con-PER, + Zn with Org-PER, + Cu with Org-PER, − Mn with Org-PER and Con-PER, − S with Org, = K, = Ca, = Fe, = Zn Con-PER and Org-Ann,	Turmel et al. (2009)

Table 1. Summary of published research on the effect of cropping system management on soil parameters and grain nutritive component outcomes, Cont.

Location	# Years	Soil	Cultivar	Cropping system○		Soil parameters measured✚	Grain components measured✣	Reference
Saskatchewan, Canada	12	Orthic Brown Chernozem, Swintom loam	*Triticum aestivum L.*	F-W-W	L_{GM}-W-W	--	＋N in years 6-12, ＝N in years 1-6	Zentner et al. (2004)
Chillán, Chile	1	Melanoxerands	*Triticum aestivum*	Can-W	B-W	Bulk density; pH; SOC; EC; available N; exchanagle K, Ca, Mg, Na, Al, Fe; available Fe, Mn, Zn, Cu, B, S	＋K, ＋Ca, ＝N, ＝P, ＝Mg, ＝S	Hirzel et al. (2020)
New South Wales, Australia	1	Kandosol	Diamondbird cultivar	F-W	Can-W, Clov-W, Lin-W	－Available P, ＋AMF with Clov-W and Lin-W, ＝AMF with Can-W	＋Zn with Clov-W and Lin-W, ＋P, ＋Fe with Can-W, －PA:Zn with Clov-W and Lin-W, ＝PA:Zn with Can-W, ＝Total polyphenols, ＝PA:Fe	Ryan et al. (2008)
Oromia, Ethiopia	1	Loam and clayey loam	*Triticum* sp. L.	Lower SOM	Higher SOM	pH, MBC, POC, PON, Mineral associated C and N	＋N with higher particulate and mineral-associated organic matter N in soil, ＋Zn with higher mineral-associated organic C in soil	Woods et al. (2018)
Isfahan, Iran	2		*Triticum aestivum* L cv. Kavir and Backcross	F-W	Clov-W, Sun-W, Grass-W, Sorg-W	＋Dissolved organic C, ＋Soil amino acids, ＋Soil microbial respiration with Clov-W and Sun-W	＋Zn	Soltani et al. (2014)
Montana, USA	2	Typic Calciustolls, Judith clay loam	*Triticum aestivum* L	F-W	W-W, P-W, L_{GM}-W, L-W	--	＋N with L_{GM}-W, ＝N with W-W, W-P, L-W	Chen et al. (2012)
Saskatchewan, Canada	3	Orthic Brown Chernozem (Aridic Haploborolls) and Rego Brown Chernozem (Vertic Cryoborolls)	*Triticum turgidum* L.	W-W-W	P-P-W, Can-P-W, P-Can-W, Can-Can-W	＋Residual NO_3-N, ＋plant available soil water with P in rotation	＋Protein	Gan et al. (2003)

Notes:

○ CT = Conventional Tillage, RT = Reduced Tillage, NT = No-Till, W-W= Continuous Wheat, F = Fallow, F_{LM}= Fallow with livestock manure, A =Alfalfa/Hay, OP_{LM} = Oat/Pea with livestock manure, GM = Green manure, L = Lentil, L_{GM} = Lentil green manure, C= Corn, B= Bean, Clov = Clover, Sun = Sunflower, Lin = Linola, Can= Canola, Sorg = Sorghum, CP= chickpea, CL/No-CL= Chicken litter/no chicken litter, Con-Ann= Conventional management rotation of wheat-pea-wheat-flax, Org-Ann= Organic managment rotation of wheat-pea-wheat-flax, Con-PER= Conventional management rotation of wheat-alfalfa-alfalfa-flax, Org-PER= Organic management of wheat-alfalfa-alfalfa-flax, NR= No removal of straw from field, R= removal of straw from field, Lower/Higher SOM= Lower/higher levels of soil organic matter

✚ The symbols preceding the soil parameter measured indicate the direction of change observed between the comparison and base management. '＋' indicates a significant increase, '–' indicates a significant decrease and '＝' indicates no significant difference was observed. Observations without a preceding symbol indicate that no comparison measurements were taken. All results significant at $P < .05$ level. SOC= Soil organic carbon, TON= Total organic nitrogen, STN= Soil total nitrogen, PON= Particulate organic Nitrogen, POC= Particulate organic carbon, PNM= potential N mineralization, LFC= Light-fraction C, LFN= Light-fraction N, MBN= Microbial biomass N, MBC= Microbial biomass C, AMF= Arbuscular mychorrhizal fungi colonization, non-MF= Non-mycorrhizal fungi colonization, EC= electrical conductivity, WSI= Water stress index, WSA= Water stable aggregates, WHC= Water holding capacity

✣ Changes in grain components observed across treatments are shown here as reported in each paper. The symbols preceding the grain component measured indicates the direction of change observed between the comparison and base management. '+' indicates an increase, '–' indicates a decrease and '=' indicates no significant difference was observed. All results significant at $P < .05$ level. PA:Zn= the ratio of phytic acid to zinc, representing the bioavailability of Zinc with a lower level of phytic acid, and thus a lower Pa:Zn ratio, indicating increased Zn bioavailabilty. PA:Fe= the ratio of phytic acid to iron, representing the bioavailability of iron, with a lower level of phytic acid, and thus a lower Pa:Zn ratio, indicating increased Fe bioavailability.

'－－' Indicates data is not available

Table 2. Summary of published research on the effect of cropping system on grain yield, protein concentration and protein content

Location	Soil	Cropping system°		Grain yield-Base	Grain yield-Comparison	Grain protein- Base	Grain protein-Comparison	Grain protein removal-Base	Grain protein removal-Comparison	Reference
		Base management	Comparison management	———(kg/ha)———		———(%)———		———(kg/ha)———		
Alberta, Canada	Dark Gray Luvisol, sandy loam	CT	NT	--	--	--	--	314.13 (CT, year 7)*, 385.00 (CT, year 8)	520.63 (NT, year 7)*, 388.75 (NT, year 8)	Lupwayi et al. (2006)
Saskatchewan, Canada	Gray Luvisol (Boralf), sandy clay loam	CT, NR	NT, R	2896* (CT), 2713 (NR)*	2694 (NT)*, 2877(R)*	15.7 (CT)*, 15.6 (NR)*	15.8 (NT)*, 15.9 (R)*	455.63 (CT)*, 424.38 (NR)*	425 (NT)*, 456.88 (R)*	Malhi et al. (2007)
Mississippi, USA	Alifsol, Loring silt loam	CT C-W, No-CL	NT C-W, CL (high application)	1269 (CT); 901 (no-CL)	1244 (NT); 1778 (CL-high application)	9.5 (CT), 9.7 (No-CL)	8.9 (NT), 9.1(CL)	120.63(CT), 87.50(No-CL)	110.63 (NT), 162.50(CL)	Adeli et al. (2017)
Oregon, USA	mesic Typic Haploxeroll, Walla Walla silt loam	CT	NT	--	--	8.97 (CT)*◇	8.26 (NT)*◇	--	--	Park et al. (2015)
Foggia, Italy	Typic Chromoxerert, clay loam	CT	NT	2940 (CT, year 6)*, 900 (CT, year 7)*, 2650 (CT, year 8)	3340 (NT, year 6)*, 1650 (NT, year 7)*, 2130 (NT, year 8)	11.6 (CT, year 6)*, 19.6 (CT, year 7)*, 15.5 (CT, year 8)*	12.8 (NT, year 6)*, 14.7 (NT, year 7)*, 11.4 (NT, year 8)*	341. 04 (CT, year 6), 176.4 (CT, year 7), 410.75 (CT, year 8)	427.53 (NT, year 6), 242.55 (NT, year 7), 242.82 (NT, year 8)	De Vita et al. (2007)
Sicily, Italy	Chromic Haploxerert	CT, W-W	NT, RT, and B-W, Clov-W	3430 (CT, W-W)*, 4230 (CT, Clov-W), 4690 (CT, B-W)*,	3110 (NT, W-W)* 4360 (NT, Clov-W), 4890 (NT, B-W)*	13.9 (CT, W-W), 15.2 (CT, Clov-W), 14.7 (CT, B-W)	13.6 (NT, W-W) 13.8(NT, Clov-W), 13.5 (NT, B-W)	476.77 (CT, W-W), 642.96 (CT, Clov-W), 689.43 (CT, B-W)	422.96 (NT, W-W) 601.68 (NT,Clov-W), 660.15 (NT, B-W)	Amato et al. (2013)
New South Wales, Australia	Grey Vertisol (V) and Red Kandosol (K)	CT	NT	1851 (CT-K), 1389 (CT-V)	1866 (NT-K), 1371 (NT-V)	10.6 (CT-K)*, 17.0 (CT-V)*	11.5 (NT-K)*, 14.5 (NT-V)*	196.21 (CT-K),236.13 (CT-V)	214.59 (NT-K), 198.90 (NT-V)	Wilkes et al. (2010)
Córdoba, Spain	Vertisol (Typic Haploxererts)	CT, W-W	NT, F-W, Sun-W, B-W, CP-W	--	--	12.38 (CT W-W), 11.96 (CT Sun-W), 12.13 (CT CP-W), 12.24 (CT B-W), 12.24 (CT F-W)	11.63 (NT W-W)*, 11.77 (NT, Sun-W)*, 12.06 (NT CP-W), 12.10 (NT B-W)*, 11.89 (NT F-W)*	--	--	López-Bellido et al. (2001)
Montana, USA	Kandosol	CT F-W	CT W-W, CT W-P, RT W-W, NT W-W	--	--	--	--	163.13 (CT W-F)*	272.50 (NT W-W)*, 252.50 (RT W-W)*, 253.75 (CT W-W)*, 255.63 (CT W-P)*	Sainju et al. (2008)
Manitoba, Canada	Rego Black Chernozem	Con-ANN	Org-ANN, Con-PER, Org-PER	2198 (Con-ANN)	899 (Org-ANN)*, 2518 (Con-PER), 1188 (Org-PER)*	15.6(Con-Ann)	13.1 (Org-ANN), 15.6 (Con-PER), 15.0 (Org-PER)	343.44(Con-Ann)	118.00(Org-ANN), 393.44 (Con-PER), 178.19 (Org-PER)	Turmel et al. (2009)
Saskatchewan, Canada	Orthic Brown Chernozem, Swintom loam	F-W-W	L_{GM}-W-W	2224	2328	13.1	15.2	291.875	353.75	Zentner et al. (2004)
Chillán, Chile	Melanoxerands	Can-W	L-W	5740 (Can-W)	6150 (B-W)*	14.4 (Can-W)	14.3 (B-W)	826.94 (Can-W)	881.38 (B-W)	Hirzel et al. (2020)
Montana, USA	Typic Calciustolls, Judith clay loam	F-W	W-W, P-W, L_{GM}-W, L-W	2136 (F-W)	1155 (W-W)*, 2193 (P-W), 1470 (L-W)*, 1835(L_{GM}-W)*	11.6 (F-W)	12.2(W-W), 11.9 (P-W), 11.9 (L-W), 12.8(L_{GM}-W)*	247.78 (F-W)	140.91 (W-W), 260.97 (P-W), 174.93 (L-W), 234.88(L_{GM}-W)*	Chen et al. (2012)
Saskatchewan, Canada	Orthic Brown Chernozem (AridicHaploborolls), and Rego Brown Chernozem (Vertic Cryoborolls)	W-W-W	P-P-W, Can-P-W, Can-Can-W	2240 (W-W-W)	2660 (P-P-W)*, 2620 (Can-P-W)*, 2630 (P-Can-W)*, 2540 (Can-Can-W)*	11.21 (W-W-W)	13.38 (P-P-W), 13.02 (Can-P-W), 12.81 (P-Can-W), 12.64 (Can-Can-W)	251 (W-W-W)	356 (P-P-W)*, 341 (Can-P-W)*, 337 (P-Can-W)*, 321 (Can-Can-W)*	Gan et al. (2003)

Notes:

° CT = Conventional Tillage, RT = Reduced Tillage, NT = No-Till, W-W= Continuous Wheat, F = Fallow, GM = Green manure, L = Lentil, L_{GM} = Lentil green manure, C= Corn, B= Bean, Clov =

* = The comparison management is significantly different from the corresponding base management at the P <.05 level

◇ = Measurement taken is percent protein in whole wheat flour

'— —' Indicates data is not available

Table 3. Summary of published research on the effect of cropping system on grain yield, zinc concentration and zinc content

Location	Soil	Cropping System○		Grain yield-Base	Grain yield-Comparison	Zn Concentration-Base	Zn Concentration-Comparison	Zn removal- Base	Zn removal-Comparison	Reference
		Base management	Comparison Management	———(kg/ha)———		———(mg/kg)———		———(g/ha)———		
Oregon, USA	Mesic Typic Haploxeroll, Walla Walla silt loam	CT	NT	--	--	14.8 (CT)◇	13.8 (NT)◇	--	--	Park et al. (2015)
Zurich, Switzerland	Dystric Gleysol	CT	RT, NT	--	--	significantly lower, not reported	significantly higher, not reported	--	--	Mozafar et al. (2000)
Alberta, Canada	Orthic Dark Brown Chernozems, loam	W-W	F-W, F-W-W, OP_{LM}-W-W, F_{LM}-W-W, GM-W-W, F-W-W-A-A-A	--	--	32.76 (W-W)	30.3 (F-W), 30.6 (F-W-W), 31.12 (OP_{LM}-W-W), 34.71 (GM-W-W), 31.29 (F_{LM}-W-W), 47.68 (F-W-W-A-A-A)*	--	--	Smith et al. (2018)
Manitoba, Canada	Rego Black Chernozem	Con-ANN	Org-ANN, Con-PER, Org-PER	2198 (Con-ANN)	899 (Org-ANN)*, 2518 (Con-PER), 1188 (Org-PER)*	40 (Con-ANN)	41 (Org-Ann), 39 (Con-PER), 47 (Org-PER)*	87.92 (Con-ANN)	36.85 (Org-ANN), 98.202 (Con-PER), 55.836 (Org-PER)	Turmel et al. (2009)
New South Wales, Australia	Kandosol	F-W	Can-W, Clov-W, Lin-W	3100 (F-W)	2600 (Can-W), 2900 (Lin-W), 2700 (Clov-W)	18.4 (F-W)	21.1 (Can-W), 24.5 (Lin-W)*, 26.1 (Clov-W)*	57.04 (F-W)	54.86 (Can-W), 71.05 (Lin-W), 70.47 (Clov-W)	Ryan et al. (2008)
Isfahan, Iran	--	F-W	Clov-W, Sun-W, Grass-W, Sorg-W	--	--	significantly lower (F-W)*	56.8–89.2% higher (cv. Backcross)*, 64.5–79.1% higher (cv. Kavir)*	significantly lower, not reported	significantly higher, not reported	Soltani et al. (2014)

Notes:

○ CT = Conventional Tillage, RT = Reduced Tillage, NT = No-Till, W-W= Continuous Wheat, F = Fallow, F_{LM}= Fallow with livestock manure, A =Alfalfa/Hay, OP_{LM} = Oat/Pea with livestock manure, GM = Green manure, Clov = Clover, Sun = Sunflower, Lin = Linola, Can= Canola, Sorg = Sorghum, Con-Ann= Conventional management rotation of wheat-pea-wheat-flax, Org-Ann= Organic managment rotation of wheat-pea-wheat-flax, Con-PER= Conventional management rotation of wheat-alfalfa-alfalfa-flax, Org-PER= Organic management of wheat-alfalfa-alfalfa-flax

* = The comparison management is significantly different from the corresponding base management at the P <.05 level

◇ = Measurement taken is percent protein in whole wheat flour

'— —' Indicates data is not available

Case Study 2: Tomato

Most of the 12 publications that compare effects of agronomic systems on tomato nutrient composition focused on comparing outcomes of organic and conventional production practices (Table 4), in contrast to the emphasis on tillage and crop rotations for wheat. Although assumptions can be made about variations in SH among these systems, the absence of soil data in many of these publications make them relevant but lacking in key data. Few papers focused on tomatoes contained information on both SH measurements and fruit nutritive outcomes (Colla et al., 2002; Koh et al., 2013; Mitchell et al., 2007; Ulrichs et al., 2008). Other papers that compared tomato fruit nutritional quality outcomes based on different organic inputs (e.g., livestock manure, green manure, mulch) described the different production practices but did not report soil parameters (Galieni et al., 2017; Toor et al., 2006). Moreover, the majority of the papers summarized here lacked yield data from the different systems, making nutrient content, rather than concentration only, beyond assessment.

The literature on tomatoes and other horticultural crops provided data on many plant secondary compounds (PSCs) relevant to human health, including phenols, flavanols, carotenoids, ascorbic acid, and other compounds with antioxidant properties (Barański et al., 2014; Reeve et al., 2016), in addition to macro- and micronutrients. The health benefits of PSCs make these papers important to the discussion on SH-human health connections (Anton et al., 2014; Chassy et al., 2006; Koh et al., 2013).

Tomato macro- and micronutrients:
Organic and conventional production systems resulted in significantly different concentrations of macro- and micronutrients in tomato fruits. After 10 years under organic or conventional management, concentrations of soil total C (STC), soil total N (STN), Ca and P were greater under organic than under conventional practices; tomato fruits produced in the organic system had significantly higher concentrations of P, lower concentrations of N and Na, and no significant differences in Ca, Mg or K. Differences in macro- and micronutrient concentrations in fruits cannot be attributed to yield effects because yields did not differ (Colla et al., 2002). Similarly, in another 10-year experiment, organic tomatoes had N and K concentration that were lower and not different, respectively, to concentrations in tomato fruits produced with conventional practices (De Pascale et al., 2016).

Nitrogen source apparently affected crop nutrient outcomes in a 1-year experiment contrasting effects of a NO3-dominant synthetic fertilizer with two organic fertilizers, chicken litter (CL) and clover green manure (Clov-GM). Data on nutrients in soil were not reported, but compared to fruits produced with inorganic N, fruits grown with either organic fertilizer had lower P concentrations. Fertilization with CL or Clov-GM resulted in significantly lower Mg or S concentration in fruits, respectively, compared to the inorganic N source. Concentrations of C, N, Ca, and K in fruits did not differ among the three N sources (Toor et al., 2006).

Tomato Plant Secondary Compounds:
Several papers described effects of production practices on carotenoids and ascorbic acid (AA), which are important vitamins found in tomatoes. Concentrations of lycopene and α-carotene were similar in ecologically or conventionally grown tomatoes (Ulrichs et al., 2008), but tomatoes from another organic system had a significantly higher concentration of these carotenoids compared to fruits from a conventional system (De Pascale et al., 2016). Fruits had significantly lower lycopene concentration when the plants had been fertilized with Clov-GM compared to a synthetic N source; concentrations were the same for fruits from plants fertilized with CL or synthetic N. Either organic fertilizer increased AA by approximately 50% on a dry-weight basis (Toor et al., 2006). However, responses to differences between organic and conventional production systems may depend on crop genetics; one tomato cultivar, but not another, had a significantly higher AA concentration on a fresh-weight basis (FWB) under organic production compared to conventional. On a dry-weight basis (DWB), however, no differences were apparent (Chassy et al., 2006).

Changes in flavonoids with antioxidant properties, specifically rutin, quercetin, naringenin and kampferol, were a common outcome in comparing organic and conventional tomatoes. Organic-produced tomatoes had significantly greater concentrations on a DWB of quercetin, naringenin and kampferol than conventionally produced tomatoes (Mitchell et al., 2007). Organic and conventional production systems induced significant differences in flavonoid concentrations (FWB only), although two cultivars responded differently (Chassy et al., 2006). In a comparison of commercial tomato juice from organic and conventional tomatoes, quercetin, naringenin, kaempferol and rutin concentrations (FWB) were greater in the organic tomatoes than in the conventional fruits (Vallverdú-Queralt et al., 2012). Although these three studies differed in methods, all provided evidence that organic and conventional production systems induced different concentrations in flavonoids in tomato fruits.

Differences between effects of conventional and organic production on the concentration of phenolic compounds in tomatoes is not consistent across publications. Ecologically grown tomatoes had less total phenolic (TP) concentration on a FWB than conventionally produced fruits (Ulrichs et al., 2008). In contrast, organic tomatoes had a greater concentration of TP (FWB) than conventional tomatoes, and as with flavonoids, tomato cultivars differed in the effect of production system on tomato phenol concentration (Vallverdú-Queralt et al., 2011). Among four tomato cultivars, only one had significantly different TP concentrations in organic versus conventional production practices; however, whether the organic fruits had the greater or lesser TP concentration varied in different years (Anton et al., 2014). Source of N fertilizer (organic vs synthetic) did not affect TP concentration (DWB) in tomatoes (Toor et al., 2006).

Similarly, evidence of free radical scavenging or antioxidant capacity is inconsistent across experiments. Source of N in fertilizer (organic or synthetic) had no effect on soluble antioxidant activities, which is consistent with results for phenolics that are important antioxidants (Toor et al., (2006). Lipophilic antioxidant capacity in organic tomatoes was greater than in tomatoes from conventional production (De Pascale et al., 2016). A similar effect occurred for hydrophilic antioxidant capacity in tomato juice (Vallverdú-Queralt et al., 2012). Organic production practices also resulted in greater concentrations of several other plant secondary compounds with potential human health promoting benefits, including two hydroxycinnamic acids (ferulic and caffeic) (Anton et al., 2014; Vallverdú-Queralt et al., 2012), and a glycoalkaloid, α-tomasine (Koh et al., 2013).

Possible mechanisms connecting soil health and tomato nutritive outcomes:
Few of the tomato studies included data for SH measurements, but some connections between soil properties and tomato nutrient outcomes are indicated. Several publications demonstrated differences in nutrient cycling and availability in organic systems where large additions of OM (e.g., livestock manure, cover crop, compost) were used to maintain adequate soil nutrient levels and crop yields. These applications of OM resulted in increases in SOM, STC, and STN (Colla et al., 2002; Koh et al., 2013; Mitchell et al., 2007).

Organic systems have greater amounts of nutrient-containing SOM than their conventional counterparts (Gattinger et al., 2012; Teasdale et al., 2007). The phytoavailability of nutrients such as N differs based on the fertilizer source, and soil nutrient cycling can influence tomato nutrient concentration outcomes. SOM may affect nutrient concentration due to improved cation exchange capacity and increased availability of nutrients through enhanced biological activity or mutualistic plant–microbial relationships (Reeve et al., 2016). Higher SOM concentrations in organic systems also changed physical properties of the soil, e.g., development of biopores, which enable root growth, increase water holding capacity, and enhance nutrient uptake (Colla et al., 2000; Reeve et al., 2016; Sainju et al., 2001).

Soil organic matter is often increased by SH-promoting practices and may affect the nutritive value of tomato fruits. Nitrogen from inorganic fertilizer may be more readily available than N from organic inputs. Organic N in OM must be mineralized to an inorganic form and may be released slowly (Colla et al., 2002; Koh et al., 2013; Sainju et al., 2001). The concentration of N in organic tomato fruits was significantly lower than in fruits from conventional systems, despite increased STN in organically managed soil (Colla et al., 2002; De Pascale et al., 2016). However, in an experiment designed specifically to assess the effect of organic vs. inorganic N fertilizer on nutrient outcomes, tomato N concentration did not differ between treatments (Toor et al., 2006). Furthermore, greater concentrations of mineral nutrients in soil did not result consistently in greater mineral concentration in the tomatoes. After 25 years of organic or conventional management at UC Davis Russel Ranch Sustainable Agriculture Facility, organic soils had significantly higher concentrations of soil Zn and Cu, while the fruits had significantly lower concentrations of both minerals compared to the conventional counterparts (Rippner and Parikh 2018). Increases in SOM from soil management practices may preferentially bind Zn and Cu, reducing bioavailability to a crop.

Hypothetically, a relationship between N availability and PSC synthesis may be caused by a mechanism involving C:N ratio, whereby low availability of N induces a shift from protein synthesis to C-based PSC synthesis (Chassy et al., 2006; Koh et al., 2013; Toor et al., 2006; Vallverdú-Queralt et al., 2012). This may explain how flavonoid concentration was greater in manure-amended organic tomatoes in the first few years of a study and then accumulated to even greater concentrations after manure applications were stopped, further reducing readily available N (Mitchell et al.,2007). Reduced N availability in soil amended with organic fertilizer also resulted in lower aboveground plant biomass, causing fruit to be increasingly exposed to sunlight (Toor et al., 2006). Increased sun exposure may have stimulated synthesis of phenolic compounds, as light exposure was an environmental control in previous studies (Toor et al., 2006). When synthetic pesticides were withheld from organic farming systems, increased pressure from pests or pathogens may have also stimulated production of PSCs that are natural defense substances for the plant (Barański et al., 2014; De Pascale et al., 2016; Reeve et al., 2016).

As with wheat grain, there is considerable interest on the effect of AMF colonization on fruit nutrient outcomes. To determine effects of AMF colonization on nutrients in tomato, a wild type cultivar (76R) and a mutant exhibiting limited fungal colonization (rmc) were planted. These cultivars permitted comparing effects of AMF root colonization without otherwise altering the environment. The rmc mutant had a significantly lower AMF root colonization of 6.8% compared to 22.5% for the wild type. Tomato yield was the same for the two cultivars, as were fruit concentrations of Ca, Fe, K, Mg, C, N and S. The wild type variety had significantly greater concentrations of Zn and P, and the rmc mutant had significantly greater concentrations of Mn and Na. The low-N condition in organic systems may have resulted in greater mining for N in the soil, aided by the increased mutualistic relationship with AMF and non-MF fungi, resulting in the uptake of other nutrients as well (Cavagnaro et al.,2006).

Table 4. Summary of published research on the effect of cropping system on soil parameters and tomato nutritive component outcomes

Location	# Years	Soil	Cultivar	Cropping System°		Soil parameters measured✚	Fruit components measured❖	Reference
				Base management	Comparison Management			
California, USA	10	Typic Xerothents, Yolo silt loam and Mollic Haploxeralfs, Rincon silty clay loam	*L. esculentum* L. cv. Halley 3155	Con	Org	+SOM*	Flavanoids: +Quercetin, +Naringenin, +Kampferol	Mitchell et al. (2007)
California, USA	10	Mollic Xerofluvents, coarse loam	*L. esculentum* Mill.	Con	Mixed, Org	+STC (Org)*, +STN (Org)*, +Ca (Org)*, +P (Org)*, +K (Org)*; =pH, =STN (Low), =Ca (Low), =P (Low), =K (Low), =Na	+P (Org), −Ca (Mixed) , −N, −Na, −Ca (Mixed), =P (Mixed), =K, =Mg, =Ca (Org)	Colla et al. (2002)
California, USA	10	Typic Xerothents, Yolo silt loam and Mollic Haploxeralfs, Rincon silty clay loam	*L. esculentum* L. cv. Halley 3155	Con	Org	+SOM*	α-tomatine	Koh et al. (2012)
California, USA	3	Reiff, very fine sandy loam	*L. esculentum* L. cv. Ropreco, Burbank	Con	Org	--	Antioxidants: +quercetin/FWB (Burbank), +kaempferol/FWB, +AA/FWB (Burbank); =quercetin/DWB, =quercetin/FWB (Ropreco), =kampferol/DWB, =TP/FWB, =TP/DWB, =AA/FWB (Ropreco), =AA/DWB	Chassy et al. (2006)
California, USA	25	Typic Xerothents, Yolo silt loam and Mollic Haploxeralfs, Rincon silty clay loam	--	Con	Mixed, Org	+Zn (Org)*, +Cu (Org)*, −Cd (Org)*, =Zn (Mixed), =Cu (Mixed)*, =Ni, =Cd (Mixed)	−Zn (Org), −Cu (Org), −Cd, −Ni (Org), =Zn (Mixed), =Cu (Mixed), =Ni (Mixed)	Rippner and Parikh (2018)
Naples, Italy	10	--	*L. esculentum* Mill., cv. Licata, CH2000, Sansome	Con	Org	--	+Lipophilic Antioxidant Capacity + Carotenoids, −N, =K	De Pascale et al. (2016)
Jogeva, Estonia	3	Soddy–podzolic sandy loam	*L. esculentum* Mill. cv. Maike, Malle F1, Gartenfreude, Valve	Con	Org	--	+TP (cv. Malle, 2010), −TP (cv. Malle, 2008), =TP (cv. Maike, Gartenfreude, Valve); +Polyphenols: phloretin dihexoside, caffeic acid hexoside I, and apigenin acetylhexoside	Anton et al. (2014)
California, USA	1	Mollic Haploxeralfs, Zamora loam	*L. esculentum* Mill. cv. 76R and rmc (mycorrhiza defective mutant)	Org, var. 76R variety	Org, var. *rmc* (mycorrhiza defective)	−AMF*, +Olsen P*, +NO_3*, =NO_4, =MBC	−Zn, −P, +Mn, +Na, =Ca, =Fe, =K, =Mg, =C, =N, =S	Cavagnaro et al. (2006)
Berlin, Germany	1	--	*L. esculentum* Mill, var. Vitella F1	Con	Eco	-pH, -STN, -K, -EC, +P	=Lycopene, =β-carotene, −TP	Ulrichs et al. (2008)
Barcelona, Spain	--	--	Commercial tomato juice	Con	Org	--	+TP, +Hydrophylic antioxidant capacity, +Flavanols (rutin, quercetin, kaempferol), +Flavanones (naringenin) +Hydroxycinnamic acid (ferulic acid), +Caffeic acid	Vallverdú-Queralt et al. (2011)

Table 4. Summary of published research on the effect of cropping system on soil parameters and tomato nutritive component outcomes

Location	# Years	Soil	Cultivar	Cropping System°		Soil parameters measured✚	Fruit components measured✜	Reference
				Base management	Comparison Management			
Uppsala, Sweden	--	--	*L. esculentum* Mill. Cv. 'Armada' Enza Zaden	Synthetic fertilizer: NO_3-dominant	Organic fertilizers: CL, Clov-GM	--	−Mg (CL) −P, −S (Clov-GM), =C, =N, =Ca, =K, =S (CL), =Mg (Clov-GM), Antioxidants: +AA, −Lycopene (Clov-GM), =Soluble phenolics, =Lycopene (CL), =Soluble anti-oxidant activity	Toor et al. (2006)
Martinsicuro, Italy	1	sandy clam loam	*Solanum lycopersicum* L.	No mulch	MuF, MuB, MuR, InF, InB, InR	--	+Ca with InF, =Ca with MuF and MuR −Ca with all other treatments, +P with MuR, =P with all other treatments, +Mg with MuF and InF, =Mg with all other treatments, =K	Galieni et al. (2017)

Notes:

✚ The symbols preceding the soil parameter measured indicate the direction of change observed between the comparison and base management. '+' indicates a significant increase, '–' indicates a significant decrease and '=' indicates no significant difference was observed. Observations without a preceding symbol indicate that no comparison soil measurements were taken. * All soil measures marked with a '*' are significantly different from the Base treatment at P <.05 level. AMF = arbuscular mycorrhizal fungi colonization, STC = soil total carbon, STN = soil total nitrogen, EC = electrical conductivity

✜ The symbols preceding the grain component measured indicate the direction of change observed between the comparison and base management. '+' indicates an increase, '–' indicates a decrease and '=' indicates no significant difference was observed. For tomato fruit components. All fruit comparison measurements reported here are significant at the P <.05 level. TP = total phenols, AA=ascorbic acid, DWB=results analyzed on a dry-weight basis, FWB=results analyzed on a fresh-weight basis

°Org= Organic management, using practices compliant with Certified Organic which includes the use of cover crops, composted manure, mechanical weed control, biological pest control, and organic-approved chemicals. Con= Conventional managment, using synthetic fertilizer and pesticides, and chemical weed control typical to that growing area/system. Mixed= Compared to conventional managment, this system uses reduced synthetic fertilizer and pesiticide application with the use of cover crops nad mechanical weed control in their place. Eco= Ecological management which is defined by the authors as the creation of optimum crop conditions and robust plants, longer distances between plants for better aeration, production grown only in the ground, an exclusive use of organic fertilizers and free of chemical pesticides. NO_3^{--}-dominant= synthetic fertilizer with a 4:1 ratio of NO_3^{--} to NO_4^{+}. CL= Chicken litter. Clov-GM= clover green manure. Var *rmc= a* tomato mutant with reduced mycorrhizal (fungal) colonization. Var 76R= the mycorrhizal wildtype progenitor (*L. esculentum* Mill. cv. 76R). PVC= polyvinyl chloride plastic mulch, MuF=faba bean mulch, MuB= barley mulch, MuR= rapeseed mulch, InF= incorporated faba bean mulch, InB= incorporated barley mulch, InR= incorporated rapeseed mulch

'— —' Indicates data is not available

Conclusions: Information gaps in wheat and tomato case studies

In the publications recovered through the Web of Science, literature on agricultural practices and the nutritive value of wheat grain research differs greatly from that for tomato fruit. These differences include nutritive compounds of interest, agronomic systems and practices compared, and the detail of data presented that allows for connecting SH-promoting practices, SH itself, and crop nutritive outcomes. Wheat publications tended to have better data for making comparisons across papers, with each paper focusing on a particular set of nutritive compounds. Most wheat publications reported both yield and nutrient concentration, allowing for comparisons of nutrient content (yield x concentration). In contrast, tomato publications were inconsistent in many ways, with few providing yield data and thus lacking information that could be extrapolated to nutrient content. Data for soil mineral nutrients were absent from papers on tomato. These shortcomings illustrate how assessment of connections between SH management and human nutrition must be supported by data from experiments designed (at least in part) for that purpose.

Although both wheat and tomato are widely produced and consumed crops, only a small number of studies allowed even just a few conclusions to be drawn. Treatment designs that compare data from a small number of specific SH-related land management practices and soil measurements are needed. Much of the wheat research (Tables 1, 2, 3) reflected this approach. However, it remains a great need for tomato and other horticultural crops. Comparisons and conclusions about the effects of organic vs. conventional management systems for tomato crops (Table 4) are difficult to clarify. The different management practices applied in aggregation, and their highly diverse and individual impacts on soil physical, chemical, and biological characteristics, render data from organic vs conventional systems highly confounded. Currently, crop nutrient outcomes in organic systems that are different from conventional systems are almost impossible to attribute to specific causal mechanisms. If SH-human health connections are to be understood, there must be greatly increased emphasis on long-term studies that monitor the effects of well-defined and controlled land management practices on SH related measurements and crop nutrient outcomes in diverse agronomic and geographic settings.

An important shortcoming of nearly all the publications assessed herein was the lack of any interpretation of the data that would translate findings at the crop level to an outcome for human nutrition and health. Although the contribution of individual compounds to human health was occasionally acknowledged, and in a few cases statistically significant changes were attributed to specific treatments, this information was rarely extrapolated into insights about how these changes might contribute to improved nutrition outcomes for individuals or populations. One notable exception to this shortcoming was the paper by Wood et al. (2018), which described model projections of the increased proportion of the population's dietary needs for Zn and protein that could be met due to increased SOM. Another was that of Chassy et al. (2006), who identified the importance of measuring tomato outcomes on both DWB and FWB for analytical and nutritional comparisons, respectively, and related the observed differences in flavonoid concentration to meaningful differences in terms of quantities of tomatoes consumed. These two papers are important exemplars of ways to advance this kind of research, which is important to considerations of the total availability of nutrients to individuals and populations. Even though management practices may lead to increases in crop nutrient concentrations, the overall quantity (content) available for consumption can decrease if other management practices or environmental conditions suppress crop yield. For example, a dilution effect can occur when modern cultivars bred for maximized yield has led to a trade-off between yield and nutrient density (Davis, 2009; Davis et al., 2004).

V. Conclusion and Recommendations

Determining the causal relationships among SH management practices, SH, crop nutrition, crop nutritive value, and human health requires much more research. Such research must include specific, carefully selected, and highly controlled or characterized aspects of soil, crop, and human nutrition-relevant variables, namely:

- defined, consistently applied SH-promoting management practices,
- relevant and methodologically consistent SH measurements,
- methodologically consistent measurements of general soil conditions (physical conditions, mineral nutrient concentrations, etc.),
- methodologically consistent crop nutrient measurements (concentrations of mineral nutrients, plant secondary compounds, proteins, and others in consumed plant tissues relevant to human health), and
- crop yield measurements.

A list of SH measurements (both measured property and measurement method) that are most relevant to assess improvements in SH across diverse environments and production systems must be identified and used consistently to understand causality in data from these kinds of experiments. Experiments, measurements, and methods should be selected specifically to enable the translation of results into meaningful implications for human health. This must be achieved by interdisciplinary research teams, including human nutrition experts, to interpret connections between agronomic data and dietary impact.

Several examples from this review illustrate the benefits of an approach that makes human health outcomes as important as agronomic outcomes. One is the focus on Zn in the wheat literature, as Zn deficiency is a worldwide concern, especially in developing countries with cereal-based diets. If research can demonstrate consistent improvements in Zn content in whole grains in response to specific SH-promoting practices, widespread application of these practices could benefit human nutrition globally (Ryan et al., 2008). For horticultural crops, research is needed to clarify which phytochemicals are most beneficial for human health and thus should be an emphasis in research designed with human health in mind. For greatest relevancy for human health, data reflecting crop nutritive value should be taken from the crop tissues that are consumed, and in the condition those plant parts are eaten (i.e., fresh or dried).

Several types of diversity must be introduced into this research. New research must include a wider range of foods, especially the global array of staple crops, to have relevance to human diets worldwide. In general, most of the publications cited herein documented agronomic trials focused on a single crop. Greater diversity in farm scale and agronomic systems, reflecting global agriculture, must also be factored into research. Literature reviewed here described research on crops produced mostly in western, industrialized agricultural systems, even though research on smallholder agriculture in developing countries is of equal if not greater importance to improving human health through nutrition. Research is especially lacking for soils and crops in Sub-Saharan Africa and South Asia, where both soil degradation and malnutrition are severe (Lal, 2009). In the United States, where more than more than half of the population meets or exceeds total grain and protein consumption recommendations, a 1% increase in grain protein concentration may not alter population nutrition outcomes (U.S. Department of Health and Human Services, 2015). However, the impact of a change of that magnitude may be significant in developing countries that rely on grains as a primary source of dietary protein.

This review covered few aspects of food security, yet food security concerns should be considered in the long term as an inspiration for SH research. More than an estimated 3 billon people experience micronutrient malnutrition in both developing and developed countries, and these widespread deficiencies should be a part of the impetus for SH research (Lal, 2009; Watson et al., 2012). Soil degradation and inadequate human nutrition are linked; assessing how SH and agricultural sustainability can ameliorate both is a worthwhile goal (Lal, 2009). Clearly, managing for improved SH will support the capacity of the soil to produce food for a growing global population. Understanding the connections among SH, crop nutrient concentrations, content, and human health is essential to guide future land management policies and practices. Further research is justified to meet sustainability and nutritional goals.

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