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Alternative Management Practices Improve Soil Health Indices in Intensive Vegetable Cropping Systems: A Review

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An increase in intensive cropping would benefit society by providing food to a growing population, and vegetable production is an excellent example of intensive cropping systems that are indeed on the rise. Vegetable cropping systems are high-input and generally require large quantities of fertilization, frequent irrigation, and repeated tillage operations. Consequently, an increase in global vegetable production may have seriously negative impacts on soil health and ecosystem services. Yet, not only maintaining but improving soil health is critical to enhancing the sustainability of food production systems. Previous agricultural research mainly focused on field crop systems and largely ignored vegetable cropping systems; consequently, this represents a conspicuous research gap, one that must be addressed in order to make progress toward sustainable food production. Here, we review the literature to gain a better understanding of how management has influenced various soil health indices (soil biology, chemistry, and physical dynamics) and to evaluate the implications for soil ecosystem services in vegetable cropping systems. We found that alternative modifications to conventional vegetable production systems, which resemble methods used in organic or conservation agriculture, tended to improve aspects of soil health. For example, soil amendments generally improved soil chemical and nutrient indices of health—soil carbon levels and nitrogen reserves in particular. Incorporation of cover crops to vegetable crop rotations tended to improve nitrogen recycling via reduced nitrate leaching risks, increased soil carbon levels, and weed suppression. Reduced tillage systems were rare, presenting an important challenge and opportunity for further improving soil health dynamics in vegetable production. Notably, adopting alternative practices generally had no effect on crop yields, which implies little risk of yield penalties when agronomic management is carefully planned. Our results indicate that future sustainable vegetable cropping systems may embody a blend between organic and conventional ideologies to better maintain or improve soil ecosystem functioning.

Keywords: soil health, vegetable production, carbon sequestration, soil nutrients, organic agriculture, organic amendments, cover crops, reduced tillage

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INTRODUCTION

One of the greatest challenges facing humanity today is the urgent need to provide nutritious food to over 9 billion people. This challenge is 2-fold because not only must food production expand and intensify, it must do so in a way that does not compromise the very ecosystem services that are necessary for life on earth. Some of the most important ecosystem services are provided by healthy soils, such as carbon sequestration, nutrient supply, and water regulation. But these ecosystem services are easily disturbed through modifications of soil physical, chemical and biological conditions with cropping intensification (Tilman et al., 2002; Power, 2010). Decades of previous research has led to great success in improving methods of crop production while minimizing impact on soil health and ecosystem services, notably, the adoption of conservation agriculture with reduced tillage, reduced frequency of fallowing, and reduced fertilizer applications via strategic crop rotations or pre-plant soil tests (Doran, 2002; Hobbs, 2007; Knowler and Bradshaw, 2007). However, these successes apply only to field crops of grain, cereal, and oilseed crops—~70% of which are produced for the purpose of animal feed (Cassidy et al., 2013) rather than nutritious crops, such as vegetables, for human consumption.

Global vegetable production is rapidly expanding (FAO, 2017) due to health guidelines that recommend an increase in vegetable consumption (WHO, 2003). However, due to vegetable crop growth requirements and inherent nutritious nature, soils under vegetable crop production are managed extremely intensively; vegetable production requires much higher inputs (such as, fertilizers, irrigation, and frequent/deep tillage operations Jackson et al., 2004; Willekens et al., 2014; Congreves and Van Eerd, 2015) compared to field crops. For some vegetable crops, very little organic matter is returned to the soil after harvest (Jackson et al., 2004; Willekens et al., 2014; Brennan and Acosta-Martinez, 2017). Consequently, vegetable production may have seriously negative impacts on soil health and ecosystem services. Unfortunately, mainstream agricultural research has largely ignored soil health in vegetable cropping systems, and this represents a conspicuous research gap; one that must be addressed in order to make progress toward feeding a growing population sustainably.

Literature on soil attributes in vegetable cropping systems may not be as prevalent as for field cropping systems, but it nonetheless exists under various guises. Vegetable agronomy research is published across a wide range of disparate fields (bioresource science, horticultural sciences, agricultural sciences, ecology, land degradation science, geochemistry, soil science, plant science, urban agriculture, etc.) which is likely a factor explaining why very few research reviews (none that we are aware of) have been conducted to comprehensively evaluate how vegetable management practices influence soil health indicators. Research on soil attributes in various vegetable crop systems must be synthesized in order to understand which type of management practices best promote soil health and long-term intensive agricultural sustainability, and to identify where gaps in our understanding exist.

Soil quality and soil health are often viewed as interchangeable terms; here we use the term *soil health* because it encompasses the *integrated and complex functions* that soils provide e.g., carbon sequestration, nutrient cycling, water regulation and filtration, and biological diversity. Soil health is a broad concept and it is challenging to measure and interpret. By examining soil with an ecological perspective, i.e., considering soil physical, chemical, and biological properties, one can approach a better understanding of the various indices of soil health.

Organic farming is often practiced through an ecological perspective (Scialabba and Müller-Lindenlauf, 2010). However, while highly contextual and dependent on crop type, organic yields are typically lower than conventional yields (Seufert et al., 2012)—a result which compromises societal or economic benefits despite potential environmental benefits of organic management. A recent global meta-analysis showed greater yield reductions for vegetable crops than for cereals, oilseeds, and fruits under organic relative to conventional management (Seufert et al., 2012). Even with considerable yield concerns, the detail remains that organic systems have a strong potential for building soil health indices such as soil fertility and organic matter (Scialabba and Müller-Lindenlauf, 2010). Thus, perhaps *a blend between organic and conventional management* is a more compelling approach to maintain or improve soil health indices while maintaining crop yields, rather than strictly organic management in vegetable cropping systems. For example, if the system is not limited by nutrient inputs perhaps organic or conservation practices are key to improving soil health indices without negatively impacting vegetable yields. Here, we pose the question whether or not alternative management practices—which may resemble organic or conservation agriculture—have the potential to improve soil health indices relative to conventional vegetable crop management, without negatively impacting crop yields. If so, to what extent and which types of alternative practices have the greatest potential for improving soil health indices? To lay the foundation for better understanding soil health in intensive vegetable cropping systems, here, we present the first review to synthesize how alternative management practices influence crop yields and soil health by evaluating soil biological indices, soil chemical composition and nutrient availability, and soil physical parameters.

MATERIALS AND METHODS

Literature representing modern and westernized vegetable cropping systems across the Americas and Europe was compiled by using electronic search engines, mainly Google Scholar, Web of Science, and institutional library search engines with a focus on field research since 2000. The literature search was conducted from August 2017 to January 2018. Keywords included: soil health, soil quality, soil health indices, soil biology, soil chemistry, and/or soil physics; and were used in combination with keywords such as: vegetable, vegetable cropping systems, horticulture, intensive agriculture, and/or intensive cropping systems. Earlier papers that fit our parameters were identified

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as citations within the compiled papers. As part of our data compilation and in preparation for data analysis, the following factors were categorized in our database: vegetable crop species, trial location, the type of soil measurements (by listing the soil physical, biological and/or chemical attributes measured), the duration of the trial in years, type of experimental manipulation (amendment, tillage, cover crop, and/or crop rotation trials) with treatments listed (**Table 1**).

Of the studies compiled in our literature database, many were included in the meta-analysis. For studies to be included in the meta-analysis, there had to be a control treatment compared to experimental treatments, and the control had to be consistently defined across studies. Since we were interested in comparing the performance of conventional practices to alternative management, we defined the control treatments for each type of experimental manipulation. The controls included: un-amended treatments, no cover crop treatments (bare or fallow), and conventional tillage treatments (plow, cultivation, or disking). These controls were compared to manipulations that were: amended with organic material, included cover crops in the rotation, and implemented reduced tillage, respectively. Data were compiled from the literature database by extracting published values that were directly available from the tables and text. We did not extract data that was in figure-form. When studies reported multiple experimental results, e.g., multi-year, multi-horizon, or multi-measurements, data selected were refined based on longest experimental treatment time, topsoil (< 30 cm), and/or most common soil properties. Data were assigned to categorical indices for physical, chemical or biological soil properties. Although the analytical methods to acquire the data may have differed, we were more focused on the overall direction and magnitude of the effect of management on each soil property. As examples, the extraction solution for pH measurements tended to vary; the measurements for soil carbon included loss on ignition and elemental analysis; soil nitrogen was measured by total Kjeldahl methods and elemental analysis methods, while nitrate data included measurements from lysimeters, extracts from ion resin membranes and from the soil. We considered total carbon and nitrogen as chemical indices rather than biological properties. For biological indices of soil health, microbial populations were determined by direct counts, colony forming units, rDNA, and phospholipid fatty acids (PLFA) while community level physiological profiles (CLPP) were primarily determined by the Biolog technique.

For the meta-analysis, we used response ratio (RR) values that described the treatment effect relative to the control. The RR values were determined as follows:

$$RR = \frac{Indicator_{treated}}{Indicator_{control}}$$

according to previously published methodology (Hedges et al., 1999; Maynard et al., 2014). The RR gives a unitless measure of treatment effects to compare across a wide array of experiments. The RR values above or below 1 indicate treatment responses greater than or lower than the control treatments, respectively. When the 95% confidence intervals of the RR mean do not overlap 1, then the treatment effect can be considered as significant.

RESULTS

Body of Literature

Of the 60 publications collected, most research relied on short-term (2 to 4-year) field experiments or built off of medium-term (5 to 10-year) trials. The majority of papers collected (78%) evaluated soil chemical indicators of soil health, while 67% measured soil biological indicators, and relatively fewer studies (24%) collected soil physical measures of soil health (**Table 1**). Chemical and nutrient indices tended to focus on soil pH, EC, soil C, and N pools; biological indices primarily included microbial biomass, PLFA profiles, and soil nematodes; while physical attributes included bulk density, soil aggregate stability, texture, and moisture dynamics (**Table 1**). The seemingly heavy focus on nutrient and microbial and aspects of soil health may signify that there is more interest in understanding how to manage chemical and biological aspects in intensively managed vegetable crop soils. However, the relatively fewer studies on soil physics may not necessarily indicate there is poor interest in maintaining the physical aspects of soil health; rather, it is possible that soil physics literature might be less likely to use the keywords we searched with (e.g., soil health, soil quality, vegetable crop systems, etc.).

As for the type of manipulations that were described in the research we reviewed, 58% of the studies focused on the influence of amendments (manure, compost, biochar, green manure, etc.), 42% evaluated the effect of cover crops, while only 18% assessed the impact of different tillage systems in vegetable crop rotations (**Table 1**). Of the reviewed research, 105 different vegetable crops were studied. Those that were studied at the highest frequency, whether in the crop rotation or the crop in focus, included solanaceous crops (tomato, pepper, eggplant, and common potato) and cole crops (broccoli, cabbage, cauliflower, Brussels sprouts, kohlrabi), followed by cucurbit crops (cucumber, squash, zucchini, melon, pumpkin), grasses (entirely sweet corn) and green/salad (lettuce, spinach, chard) crops (**Figure 1**). Root (carrot, sweet potato, beet), bulb (onion, garlic), and pulse crops (bean, pea) occurred at a relatively lower frequency (**Figure 1**). Our results from these studies were determined by evaluating the RR of alternative management vs. conventional management and were deemed significant when their 95 % confidence interval did not overlap with 1. While numerous studies indicated the collection of soil health indicator data and met our criteria for inclusion in the meta-analysis, not all fully reported these data. **Table 1** indicates which studies were included in the meta-analysis, and the number of comparisons that were used for the meta-analysis for each soil health indicator is presented as a number within the symbols on **Figures 2**, **3**.

Alternative Management

Alternative management practices were defined as practices that generally deviated from conventional operations such as

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TABLE 1 | Summary of reviewed literature.

	References	Crops	Location of focus	Soil health measurements			Management manipulations			Included in meta-analysis
				Physical	Chemical	Biological	Tillage	Amendment	Cover crops	
1	Abawi and Widmer, 2000		Review			Nematodes				
2	Agneessens et al., 2014	Cole crops and other vegetables	Review		NO_3^- leaching					
3	Alliaume et al., 2013	Tomato, sweet pepper, onion, garlic, sweet potato	Uruguay	Soil texture, bulk density, porosity, gravimetric water, aggregate stability	Cation exchange, pH, soil organic C, P, K			Systems redesign included manure amendments		
4	Altieri et al., 2011	Tomato, beans	Brazil				Minimal tillage		Vetch, fodder radish, rye mixtures, fallow	✓
5	Andrews et al., 2002	Tomato, wheat, safflower, dry beans	California, USA	Water use	Total C, total N, P, K, Ca, Mg, S, Zn, NO_3^-, NH_4^+, potentially mineralizable N, EC, pH	Phospholipid fatty acids, crop yield, weed cover	Conventional vs. reduced tillage	Composted animal manure	Winter cover crops	
6	Andrews et al., 2002	Tomato, wheat, corn, safflower, beans, oats	California, USA		Total C, total N, P, K, Ca, Mg, S, Zn, NO_3^-, NH_4^+, potentially mineralizable N, EC, pH	Phospholipid fatty acids, crop yield, crop quality, weed cover		Composted animal manure	Winter cover crops	
7	Bandick and Dick, 1999	Corn, broccoli, wheat, fescue	Oregon, USA		Soil organic matter, total organic C, total N, cation exchange capacity, pH	Microbial biomass, enzyme activities			Rye/pea, red clover, rye, fallow, fescue, wheat	✓
8	Baum et al., 2015	Diverse crops				AMF				
9	Belfry et al., 2017	Tomato	Ontario, CA		Organic matter, P, K, Ca, Mg, CEC, NO_3^-, NH_4^+, pH	Crop yield			Oat, winter rye, oilseed radish, oilseed radish-rye mix, no cover control	✓
10	Bending et al., 2004	Vegetable-cereal rotation (potato, cabbage, onion, carrot, leek, grass, cereal)	Warwickshire, UK		Total organic C, total N, water soluble carbohydrate, soil mineral N, light fraction organic C and N, labile organic N, dissolved organic C	Microbial biomass N and C, basal respiration, microbial ATP, AMF colonization potential, enzyme activities Biolog metabolic profile		Organic vs. conventional fertilizer		✓
11	Beniston et al., 2016	Tomato, Swiss chard, sweet potato	Ohio, USA	Bulk density, aggregate stability, texture	pH, cation exchange, Pb, As, Cd, total C and N, nutrients	Microbial biomass C		Compost and biochar	Rye, sorgum-sundangrass	✓
12	Bonanomi et al., 2014	Kohlrabi, melon, sweet pepper, lettuce	Salerna, Italy		EC, pH, CEC Ca^{2+}, Mg^{2+}, K^+, Na^+, available P, organic C, and total C, mineral N	Dehydrogenase activity, phosphatase, beta-glucosidase, soil respiration, microbial biomass, urease activity		Compost (municipal solid waste), wood scraps from poplar		✓

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TABLE 1 | Continued

	References	Crops	Location of focus	Soil health measurements			Management manipulations			Included in meta-analysis
				Physical	Chemical	Biological	Tillage	Amendment	Cover crops	
13	Baumann et al., 2013						Minimal tillage, no-till, strip-tillage, conventional tillage			
14	Brainard et al., 2013		Review				Minimal till, strip-tillage, no-till			
15	Brennan and Acosta-Martinez, 2017	Lettuce, spinach, broccoli	California, USA		Organic carbon	Microbial biomass N and C, microbial community analysis (FAME), sequencing		Yard waste compost	Legume-rye, rye, mustard	
16	Brennan and Boyd, 2012	Lettuce, spinach, broccoli	California, USA			Cover crop biomass			Rye, legume-rye mix, mustard mix	
17	Collange et al., 2011		Review			Nematodes				
18	Congreves and Van Eerd, 2015	Cole crops and other vegetables	Review		N dynamics			Various amendments		
19	Congreves et al., 2014	Broccoli	Ontario, CA		Total N, mineral N, organic N, ^{15}N	Microbial biomass N		Used cooking oil		
20	Congreves et al., 2013	Broccoli	Ontario, CA		Mineral N			Used cooking oil, yard waste, wheat straw		
21	Creamer and Baldwin, 2000		North Carolina, USA		Total N, C:N	Total crop biomass, weed suppression, degree of nodules			Various summer cover crops	
22	D'Hose et al., 2014	Brussels sprouts, potato, fodder beet, forage maize	Belgium	Bulk density, penetration, aggregate stability	Total organic C, total organic N, extractable C, P, K,	Microbial biomass, earthworms, nematodes, ergosterol		Compost		
23	Dogliotti et al., 2014		Uruguay							
24	Drewry et al., 2015	Vegetable gardens vs. drystock, dairy, forest, natural	New Zealand	Bulk density, macro-porosity	pH, C:N, total C and N, mineral N, NO_3^-, NH_4^+, P					
25	Dumontet et al., 2017	Tomato	Valenzano, Italy	Particle size, texture class	pH, EC, total carbonate total organic C and N, C:N, total P, available P, K	Biolog substrate use, microbial DNA		Biochar, different composts, organic fertilizer		✓

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TABLE 1 | Continued

	References	Crops	Location of focus	Soil health measurements			Management manipulations			Included in meta-analysis
				Physical	Chemical	Biological	Tillage	Amendment	Cover crops	
26	Evanylo et al., 2008	Pumpkin, bell pepper, corn, rye	Virginia, USA	Bulk density, porosity, water holding capacity, runoff	Soil mineral N, extractable P, C:N, NO_3^- leaching			Fertilizer, compost, poultry litter, un-amended control, barley straw mulch		✓
27	Ferreras et al., 2006	Broccoli, lettuce	Argentina	Soil aggregates	pH, EC, soil organic C, total N	Microbial respiration		Vermi-compost (household, horse and rabbit manure), chicken manure, un-amended control		✓
28	Ferris et al., 2012	Broccoli, lettuce	California, USA		Organic C	Nematodes, crop yield		Pelleted poultry, fish emulsion Green-waste compost		
29	Gardner and Sarrantonio, 2012	Broccoli, winter squash	Maine, USA			Root length, density			2-year cover crop, alternate- year cover crops, species: red clover, winter rye, oat-vetch, oat-pea	
30	Hepperly et al., 2009	Maize, spinach, or bell pepper, small grain	Pennsylvania, USA		Total organic C, total N, NO_3^-, plant tissue N and C			Compost, manure, synthetic fertilizer		✓
31	Jackson et al., 2003		California, USA		Mineral N, acetylene inhibition, CO_2 fluxes	Phospholipid fatty acids, microbial biomass C and N	Rototill, disk			
32	Ketcheson, 1980	Corn (field corn)	Ontario, CA							
33	Leavitt et al., 2011	Tomato, bell pepper, zucchini	Minnesota, USA		Extractable P and K, organic matter, NO_3^-, NH_4^+		Roll-crimp cover crop		Winter rye, hairy vetch, mix, no-cover control	✓
34	Maltais-Landry et al., 2015	Tomato, corn, broccoli	California, USA		Hedley P fractions	Microbial biomass P, Crop yield, and tissue P content		Mineral fertilizer, yard compost, poultry manure	Rye, legume-rye mix, mustards, fallow control	
35	Maltais-Landry et al., 2016	Tomato, wheat, corn, broccoli	California, USA		Acid digestion P, P use efficiency	Crop yield		Fertilizer, mixed fertilizer, green manure	Rye, legume-rye mix, mustards, fallow control	
36	Marinari et al., 2015	Tomato	Rome, Italy	Texture	pH, total organic C, total N, carbonates	Microbial biomass C, enzyme activities			Hairy vetch, lacy phacelia, white mustard, cover crop mulching	✓

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TABLE 1 | Continued

	References	Crops	Location of focus	Soil health measurements			Management manipulations			Included in meta-analysis
				Physical	Chemical	Biological	Tillage	Amendment	Cover crops	
37	Masiunas, 1998		Review							
38	Maul et al., 2014	Tomato	Maryland, USA			DNA			Hairy vetch, rye	✓
39	McDaniel et al., 2014		Review		Total C and N	Microbial biomass C and N				
40	Mkhabela and Warman, 2005	Potatoes, corn	Nova Scotia, CA		Extractable P, pH	Crop biomass, yield		Municipal solid waste compost, synthetic fertilizer		✓
41	Morra et al., 2010	Tomato, snap, bean, lettuce	Italy	Bulk density	Total C, NO_3^-	Crop yield and biomass, soil respiration, acid phosphatase hydrolase		Compost and fertilizer		✓
42	Nair and Ngouajio, 2012	Tomato	Michigan, USA		Organic carbon, Ca, K, Mg, CO_2 fluxes, mineral N	Biolog, nematodes		Dairy compost	Rye, hairy vetch	
43	Ninh et al., 2015	Potato, corn	Michigan, USA		NO_3^-, NH_4^+, pH Total organic C, total N	Common scab, microbial biomass, enzyme activities		Poultry manure	Rye	✓
44	Ozores-Hampton et al., 2011	Cucumber, broccoli, eggplant, squash, tomato, watermelon, peppers	Florida, USA	Soil moisture, bulk density	Total N and C, Ca, Mg, P, K, Cu, Mn, Fe, Zn, trace metals, pH, EC	Number and richness of bacteria groups		Municipal solid waste, yard trimmings		✓
45	Pieper et al., 2015	Tomato, lettuce, carrot, cucurbits, cabbage	Rhode Island, USA		Cornell soil health test, soil nitrate	Soil respiration, crop yield and marketability	Strip tillage, perennial living mulch, annual living mulch, conventional tillage			
46	Roper et al., 2017	Corn, peanut, cotton, soybean, sweet potato, cabbage	North Carolina, USA		Cation exchange capacity, humic C		Tillage, no-till			✓
47	Saini and Grant, 1980	Potato	New Brunswick, CA; Maine, USA							
48	Schutter et al., 2001	Broccoli, sweet corn, green bean, cauliflower	Oregon, USA	Particle size	Total organic C, cation exchange capacity, pH	Total bacterial and fungal counts, bacterial and fungal biomass, nematodes, FAME, substrate utilization potentials, Biolog assay			1 to 9-years of winter cover cropping vs. winter fallow (cover crops such as triticale, winter pea, mix, no cover crop)	✓
49	Smith et al., 2016	Cole crops (broccoli, cabbage, cauliflower)	California, USA		Total N, mineral N			Synthetic fertilizer		

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TABLE 1 | Continued

	References	Crops	Location of focus	Soil health measurements			Management manipulations			Included in meta-analysis
				Physical	Chemical	Biological	Tillage	Amendment	Cover crops	
50	Suddick and Six, 2013	Leaf lettuce, bell bean, bell pepper, Swiss chard			pH, total C, and N, mineral N, N gas fluxes			Compost, biochar		✓
51	Thorup-Kristensen et al., 2012	Carrot, lettuce, onion, white cabbage	Denmark		N, P, K, S, NO_3^-, NH_4^+,	Root by mini-rhizotron, crop yields		Conventional fertilizer, slurry		
52	Tilman et al., 2002		Review							
53	Tonitto et al., 2006		Review						Fallow, non-legume, and legume species	
54	Tsiafouli et al., 2015		Scania, Sweden; Chilterns, UK; Czech Republic; Kria Brisi, GR			Earthworms, mesofauna, nematodes, protozoa, enchytraeids, phospholipid fatty acids	Low intensity grassland, medium intensity (tilled every 2-years), high intensity (tilled annually)			
55	Ugarte et al., 2013		Illinois, USA		Particulate C and N, potentially mineralizable N, hydrolysable N	Microbial heterotrophic activity, nematodes		Raw dairy or composted dairy	Perennial crop rotation	
56	Ugarte and Wander, 2013	Tomato, broccoli, Austrian winter peas, winter squash	Illinois, USA		Total organic C, total N, P, K, Ca, Mg, particulate C, potentially mineralizable N, hydrolysable amino NH_4^+, pH	Fluorescein diacetate		Cover crop and composted dairy manure, raw dairy manure, cover crop only	Hairy vetch, Austrian winter peas, hay, and pasture mix	
57	Wang et al., 2014	Zucchini	Hawaii, USA		Total N, NO_3^-, NH_4^+, P, K, Ca, Mg, Na, Fe, Mn, Zn, Cu, B, humic acid soil pH, EC	Nematodes		Compost, organic fertilizer (chicken manure vericompost)	Sunhemp, crimson clover, combination, and fallow	✓
58	Warman, 2005	Many	Nova Scotia, CA		Total C and N, cation exchange capacity, EC, P, pH	Crop yields				
59	Willekens et al., 2014	Broccoli, carrots, leeks	Belgium	Bulk density	pH, total organic C, soil cations, water extractable organic C	Phospholipid fatty acids	Reduced tillage	Compost		
60	Wyland et al., 1996	Broccoli	California, USA	Soil moisture	NO_3^-, NH_4^+, mineralizable N, organic C, ion exchange resins, lysimeter N	Microbial biomass C and N, above-ground crop biomass, root biomass, sclerotia, mites, symphylans, springtails			Phacelia, merced rye, or fallow	✓

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applying organic amendments, integrating cover crops into the crop rotation, or implementing methods of reduced tillage. Crop rotation was included within the experimental framework of all of the literature we reviewed but not as a main treatment effect. Hence, we did not focus the effect of crop rotation on soil health indices, but rather we focused on the effects of other treatments implemented within various crop sequences and rotations. The results of these practices were first considered in aggregate and, by and large, the results from our meta-analysis demonstrate that alternative management positively influences soil health indices (**Figure 2**). For instance, desirable affects surfaced due to alternative management, such as: reduced soil bulk density, increased soil porosity, increased soil water holding capacity, increased soil aggregate stability, increased soil carbon and nitrogen reservoirs, increased microbial indices (activity and community diversity), and reduced weed pressure. Notably, alternative management did not significantly influence vegetable crop yields (**Figure 2**).

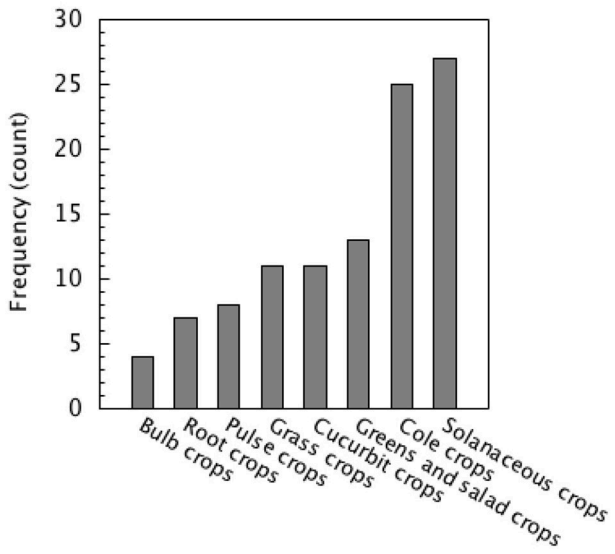

FIGURE 1 | Frequency of various vegetable crops that were evaluated in the literature; classified according to use, botany or a combination of use/botany.

Amendments

Organic carbon amendments tended to change soil properties in vegetable cropping systems (**Figure 3**) and were the main driver for improved soil health indices observed in our aggregate meta-analysis (**Figure 2**). The breadth of amendment types that were studied reflects the diversity of organic carbon material available for potentially improving soil health; ranged from various types of composts (plant-based, manure, or vermi-compost) (e.g., Morra et al., 2010), to biochar (e.g., Dumontet et al., 2017), and to used cooking oil (e.g., Congreves et al., 2014). There were also a variety of intended purposes for applying these amendments to soils in vegetable production, such as hypothesized improvements in soil organic matter levels (Morra et al., 2010), potential enhancements in microbial diversity (Dumontet et al., 2017), and reductions in postharvest N losses (Congreves et al., 2014).

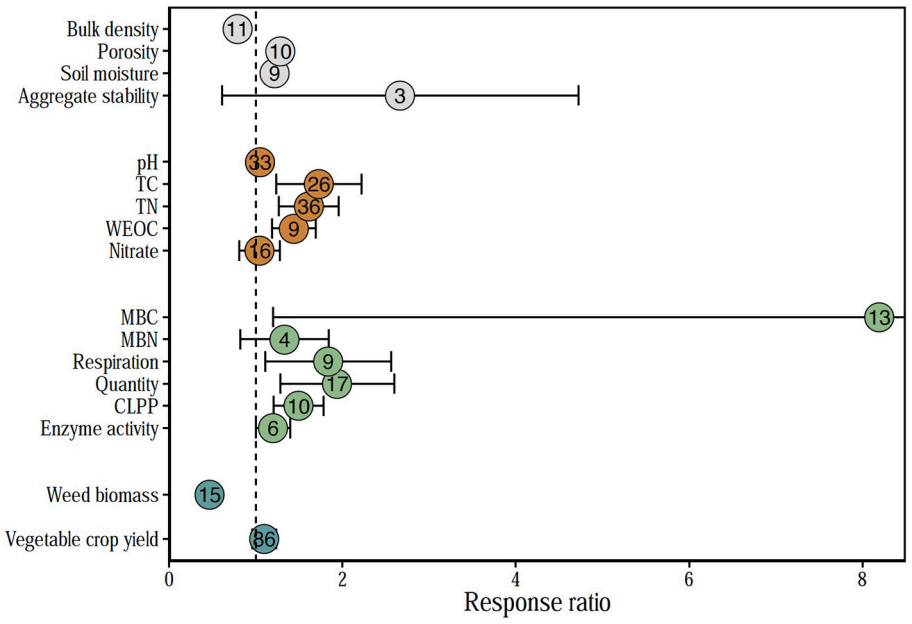

FIGURE 2 | Effects of alternative management practices on soil physical, chemical and biological properties as indicators of soil health. All points are presented as Response Ratios (RR) with the 95 % confidence interval and the respective number of comparisons *(n)* presented inside the circle. TC, total carbon; TN, total nitrogen; WEOC, water extractable organic carbon; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; CLPP, community level physiological profile.

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Although relatively few studies focused on the soil physical aspects of soil health, when physical attributes were reported, there was a general improvement (**Figure 3**) including: decreased soil bulk density (0.79 RR), increased soil porosity (1.28 RR), and increased soil moisture (1.22 RR). A greater number of organic amendment studies reported data on soil chemical properties than soil physical properties. Meta-analysis of these data clearly indicated that amendments tended to increase soil carbon levels (2.04 RR; **Figure 3**). However, the soil nitrogen indices sometimes remained unchanged (Suddick and Six, 2013), or were sometimes increased (Warman, 2005; Ferreras et al., 2006; Hepperly et al., 2009; Beniston et al., 2016) therefore our results did not indicate as large an increase in RR (1.80) for total nitrogen or soil nitrate (1.23 RR) as for total carbon (**Figure 3**).

Soil microbial biomass was a commonly studied attribute and it was found to significantly increase due to additions of organic amendment (14.25 RR), although there was considerable variability among amendment trials (**Figure 3**). Other measures of biological activity, such as heterotrophic colony forming units, microbial respiration, Biology substrate use, Biology species identification, and PLFAs were used to determine changes to soil health following amendments and, when reported, were found to have results greater than their conventional management treatment (RR $>$ 1) (**Figure 2**). Of interest, it was CLPP results which indicated significantly different soil biological activity under alternative management relative to conventional practice (**Figure 3**). Finally, our meta-analysis suggested that vegetable crop yields were significantly greater due to organic carbon amendment (**Figure 3**).

Cover Crops

Common cover crops included grasses (e.g., winter rye), legumes (e.g., hairy vetch, Austrian winter pea), brassicas (e.g., fodder radish), or mixtures of two or three of these types (Bending et al., 2004; Altieri et al., 2011; Belfry et al., 2017). Frequently, cover crops were planted following summer vegetable harvest with cover crop termination in the subsequent spring prior to planting. However, there were also cases where cover crops were planted as short-season summer crops to provide weed suppression and to supply soil nitrogen credits for fall-planted vegetable crops in the southeastern USA (Creamer and Baldwin, 2000).

Based on our literature review and meta-analysis, incorporating cover crops generally improved certain aspects of soil health compared to the conventional practice without cover crops (**Figure 3**). Soil chemical indicators of pH and soil carbon for cover crop treatments were not different from conventional management practices (RR = 1). However, soil total nitrogen levels were significantly greater (1.14 RR) with vs. without cover crop treatments, while soil nitrate measurements were significantly lower under cover cropping than their conventional management counterparts (0.64 RR) (**Figure 3**). Unfortunately for this meta-analysis there were no reports of soil physical properties with cover crop treatments.

Of the cover crop research collated here, 60% reported some measure of soil microbial biomass but no straightforward or significant response emerged (**Figure 3**). Cover crops sometimes increased microbial biomass (Wyland et al., 1996; Bandick and Dick, 1999; Maul et al., 2014; Brennan and Acosta-Martinez, 2017), decreased it (Bending et al., 2004), and mixed results were otherwise observed (Schutter et al., 2001; Marinari et al.,

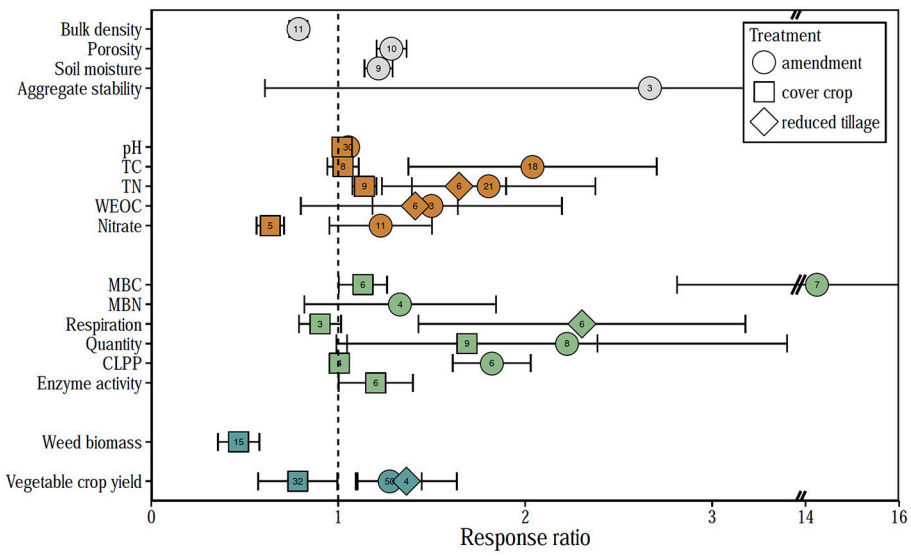

FIGURE 3 | Effects of alternative management practices on soil physical, chemical and biological properties as indicators of soil health separated by management treatment (organic amendment, cover crop, reduced tillage). All points are presented as Response Ratios (RR) with the 95% confidence interval and the respective number of comparisons *(n)* presented inside the circle. TC, total carbon; TN, total nitrogen; WEOC, water extractable organic carbon; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; CLPP, community level physiological profile.

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2015). This variable response for soil biological properties contributed to a lack of significant differences between cover crop and conventional management for various biological activity indicators such as soil respiration RR < 1, CLLP RR = 1 and RR > 1 for enzyme activity and microorganism quantity. In contrast to the soil biological results, including cover crop in vegetable cropping systems clearly decreased weed pressure (0.47 RR). While vegetable crop yields were lowered due to the presence of cover crops in the system (0.78 RR), the yield reduction was not significant (**Figure 3**).

Reduced Tillage

Of the studies we reviewed, few investigated the effects of tillage practices on intensive vegetable cropping systems (**Table 1**) and only one study fully reported their soil attribute results (Roper et al., 2017). Data from Roper et al. (2017) was included in our meta-analysis because it encompassed numerous long-term trials. Based on Roper and colleagues' work, reduced tillage significantly increased soil total nitrogen (1.65 RR), soil microbial respiration (2.30 RR) and crop yield (1.36 RR) compared to more intensive and conventional tillage practices (**Figure 3**).

DISCUSSION

Crop Rotation

Undesirable and negative implications of continuously cropping the same species year after year are well documented, such as declined levels of soil organic matter, decreased aggregate stability, increased soil bulk density, increased soil erosion, increased disease prevalence, reduced crop yields, etc. (Ketcheson, 1980; Saini and Grant, 1980; Mohr et al., 2011; Munkholm et al., 2013; Agneessens et al., 2014; McDaniel et al., 2014; Gaudin et al., 2015; Tiemann et al., 2015). Consequently, crop rotations have been consistently recommended as a best management practice to improve production and help conserve soil quality (Doran et al., 1996; Karlen et al., 1997; Doran and Zeiss, 2000; Tilman et al., 2002). Yet, recent demand for biofuel production may pressure farmers to continuously cultivate the same high-energy crop year after year; there is potential that continuous cropping may increase in the future, despite the negative consequences on soil (McDaniel et al., 2014). Currently, it remains common practice to implement crop rotations in vegetable cropping systems, as reflected in all the studies compiled for this review.

Amendments

Our meta-analysis demonstrated that vegetable crop yields were significantly increased due to organic carbon amendments (**Figure 3**), likely a result of the additional nutrients supplied with the amendments and the improved soil and growing conditions provided. One compost amendment study even concluded that there was a causal relationship between a soil quality index and the yield of potato and beets (D'Hose et al., 2014). Based on the reviewed literature, all studies reported increased or similar crop yields with soil amendments compared to the un-amended controls—expect one. The distinctive case involved potato and corn production on sandy loam in Nova Scotia with municipal solid waste compost amendments compared to standard fertilizer applications; the authors suggested that mixing the compost with inorganic fertilizer would likely alleviate nutrient limitations and yield penalties (Mkhabela and Warman, 2005).

After 9-years of annual organic carbon amendments, heterotrophic colony forming units increased by 5-fold on a sandy soil in Florida (Ozores-Hampton et al., 2011). Not only was there increased microbial activity, but microbial populations were more likely to oxidize a wider range of carbon substrates when amendments were applied to a tomato rotation, compared to an un-amended control on a silty loam soil in Valenzano, Italy (Dumontet et al., 2017). The only case where an amendment decreased microbial biomass was for a relatively low application rate of poultry litter (Ninh et al., 2015).

The large RR and variation for soil microbial biomass (**Figures 2**, **3**) was primarily due to the inclusion of an urban soil restoration study (Beniston et al., 2016). What might have been interpreted as outliers for soil microbial biomass or some physical attributes are essentially an extreme, but nonetheless important, case of soil restoration where land was converted from abandoned urban housing lots to intensive vegetable agricultural in Ohio (Beniston et al., 2016). These results emphasize the positive influence organic carbon amendments on soil physical properties. In their 1-year trial, the un-amended control had a bulk density of 1.46 Mg m^{-3} with only 0.30% water stable aggregates, while the compost amended soil (15 kg m^{-2} of composted leaves and grass clippings) decreased the soil bulk density to 1.05 Mg m^{-3} and increased soil aggregation to 0.49% (Beniston et al., 2016). Making use of urban soils for local food production is a unique niche for vegetable systems—one that this is increasing in popularity and demand; thus, represents an important and timely direction for new research on soil health.

Interpreting the influence of amendments on soil inorganic nitrogen (i.e., NO_3^-) measurements can be challenging. In some cases, greater inorganic concentrations after amendment applications were interpreted as beneficial for soil health, i.e., greater nitrate availability for plant growth (Ninh et al., 2015), but in other cases it was interpreted as increased potential for nutrient losses with a negative impact on the environment (Evanylo et al., 2008). A number of studies explored how carbon amendments immobilize inorganic nitrogen during periods when there is a high risk of nitrogen loss (Congreves et al., 2013, 2014; Congreves and Van Eerd, 2015). A finer-scale understanding of how amendments influence the *temporal dynamics* for soil inorganic nitrogen availability is key for linking its influence to aspects of soil health i.e., enhancing nutrient reservoirs for plant growth, improving nitrogen sequestration for mitigating losses to the environment, and the balance between these soil functions, etc.

Manure amendments in vegetable cropping systems were commonly researched (**Table 1**). In some cases, poultry manure amendments increased soil inorganic nitrogen levels during the growing season, which translated to increased vegetable crop yields (Ninh et al., 2015). Yet, due to the nitrogen rich and the readily mineralizable nature of poultry manure (i.e., low C:N ratios), others cautioned an increased potential for nitrate leaching after poultry litter amendments, and suggested

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that poultry litter should be mixed with other high carbon material (i.e., compost, yard waste, leaves) to reduce the risk for nitrogen losses (Evanylo et al., 2008; Hepperly et al., 2009). Although poultry manure tends to be a rich source of nitrogen, which may bode well for offsetting fertilizer demands for vegetable crops—and most tend to require high levels of nitrogen fertilizer (Congreves and Van Eerd, 2015)—it may also prime soil microbial biomass, resulting in excess mineralization of soil nitrogen stocks (Fontaine et al., 2003). Mixing poultry manure with higher C:N material, such as composted material, may promote a more moderated mineralization response sufficient for crop production.

Cover Crops

Cover crops are plants that are grown between the periods when main cash crops are produced (when the soil would otherwise be left bare) for purposes other than harvesting for direct commercial value, i.e., for altering soil physical, chemical or biological properties, to minimize erosion, or to improve soil fertility. While it has been long known that cover crops can influence soil properties (Masiunas, 1998), there are a number of variables that determine the resulting effects, such as the species mixture and composition, frequency of cover crops in rotation, timing of planting, timing of termination, surface-placed vs. incorporation of cover crop residues, selection of species that overwinter vs. winterkill in cold climates, different growth forms or nutrient acquisition strategies, etc.

Our findings agree with a previous literature review focused on cover crops by McDaniel et al. (2014) that included field crops and vegetable crops. However, based on our analysis, the influence of cover crops on most biological aspects of soil health were not marked (**Figure 3**). Although not always representative of total microbial biomass, the diversity of soil microorganisms might be more important for soil health by providing either redundant or distinct microbial functions for decomposition and nutrient cycling. Interestingly, after a 5-year conversion from conventional to organic vegetable production—which included cover cropping—the soil microbial biomass was similar or lower under organic compared to the conventional management but the functional diversity of the microbial communities differed (Bending et al., 2004). Changes in microbial community are likely driven by a number of factors; recent research demonstrated successional changes are driven by season, by location within the soil profile (i.e., bulk soil or rhizosphere), and by the previous crop (Maul et al., 2014). Not only were there quantitative differences in bacterial (16s) rDNA in an intensively managed tomato system (Maul et al., 2014), but there were also differences in soil microbial community structure when vegetables were produced after rye or vetch cover crops compared to plastic mulch without a cover crop (plasticulture being a common practice for vegetable cropping systems). However, despite the changes in soil biological indices, it did not translate into differences in subsequent tomato yield (Maul et al., 2014). Thus, soil management may influence certain aspects of soil functioning (i.e., the microbial functional diversity underlying nutrient cycling) without influencing other aspects of soil functioning (i.e., crop production), emphasizing the complex interplay among factors that regulate various capacities of the soil to function.

An earlier meta-analysis focused on cover crops primarily in field cropping systems (though a small number of vegetable trials were considered) demonstrated reductions in soil nitrate leaching due to cover cropping (Tonitto et al., 2006). In the Northern Hemisphere, cover crops are generally seeded in the fall after the main crop is harvested. Oftentimes, this period coincides with relatively high soil nitrate concentrations due to readily mineralizable and N-rich crop residues (Congreves and Van Eerd, 2015), depending on soil type and land use legacy. In Salinas Valley broccoli production, Wyland et al. (1996) nicely illustrated the seasonal fluctuations in soil nitrate concentrations and the effect that cover cropping (lacy phacelia and rye cover crops) had on reducing nitrate leaching compared to conventional practices (fallow) (9.1 and 7.4 vs. 25.5 g NO_3^--N leached m^{-2}, respectively) using ion exchange membranes. By reducing the potential for nitrate leaching and by conserving nitrogen that would have otherwise been lost, cover crops may indirectly provide nitrogen credits to subsequent vegetable crop production.

Greater yields were observed when broccoli was produced after cover cropping compared to the conventional practice in Salinas Valley, without imposing increased financial costs (Wyland et al., 1996). Similarly in Brazil, vegetable yields were equivalent to or higher with cover crops vs. without (Altieri et al., 2011); in eastern Canada, growing cover crops in a tomato rotation resulted in greater crop profit margins (Belfry et al., 2017) and 7–22% greater crop yields (Chahal and Van Eerd, 2018) compared to conventional management without cover cropping. The yield benefits were likely due to soil nutrient credits provided from the mineralization of cover crop biomass prior to or during tomato production (Belfry et al., 2017). Further, the tomato yield benefits with vs. without cover crops in the crop rotation after 6-years were linked to 8.4–9.3% greater surface soil organic carbon concentrations (Chahal and Van Eerd, 2018). Decreased weed abundance might also contribute to yield benefits, as cover crop mulches may provide a physical barrier to weed growth and thereby improve vegetable crop production (Altieri et al., 2011). Thus, cover crops may benefit multiple soil health functions such as carbon sequestration, mitigating nutrient losses and supporting crop production. Measuring mulitiple soil ecosystem functions and interpreting the influence of cover cropping is not straightforward, however; commercial "overall soil health" tests (such as the Haney Soil Health Test, the Solvita Test, and the Solvita Labile Amino N Test) may not be the most appropriate method, as suggested by Chahal and Van Eerd (2018).

Despite the potential for vegetable yield benefits due to cover crops, we found a number of observations where vegetable crop yields were reduced due to cover cropping (**Figure 3**). Instances of reduced vegetable crop yields were largely associated with a very short period between cover crop termination and subsequent main crop planting (i.e., vegetable main crops were planted immediately upon cover crop termination), and where there was a marked shift in typical crop planting dates (i.e., a delay of 2–5 weeks after recommended planting dates) (Leavitt et al., 2011). In contrast, the studies which did not show yield penalties (Wyland et al., 1996; Altieri et al., 2011; Belfry

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et al., 2017) were within the window of typical planting dates but also incorporated a strategic 2 to 6-week period between cover crop termination and main crop planting, which likely improved synchrony between mineralization and crop nutrient demand without delaying recommended crop planting dates. Hence, carefully planning agronomic management of cover crop termination and the timing of subsequent vegetable crop planting may be a determining factor in the successful use of cover crops.

Tillage Systems

Intensive tillage has long been recognized as detrimental to soil health (Carter and Sanderson, 2001; Carter et al., 2009), especially soil physical changes (Jackson et al., 2003). Few articles specifically investigated tillage effects, or explored alternate tillage impacts on soil health indices or crop production in vegetable cropping systems—only five of 60 articles focused on the topic (**Table 1**). Conservation tillage is difficult to implement in intensive vegetable cropping systems for a number of reasons including: the importance of close soil contact for seed germination, importance of tillage for weed management, and the interference of surface stubble or crop residues with transplant machinery. Despite these issues, Brainard et al. (2013) presents a thoughtful introduction on converting from conventional to reduced tillage (chisel, strip, and no-till) in vegetable cropping systems.

Soil health indicators (e.g., aggregate stability) improved with strip-tillage in a silt loam trial on Rhode Island and, while decreased vegetable yields were noted, the authors posit that improved weed management in their strip tillage treatment might have lessened yield reductions (Pieper et al., 2015). Reduced tillage has been suggested as a viable alternate to conventional tillage in vegetable cropping systems in North Carolina, possibly leading to improved soil conditions (Roper et al., 2017). However, soil health tests such as the Cornell Soil Health Test and the Haney Soil Health Test were unable to distinguish amongst long-term intensive vs. conservation tillage practices (Roper et al., 2017), suggesting the sensitivity of such tests to changes in management may be limited—a finding that echoes the conclusions drawn by Chahal and Van Eerd (2018) for cover cropping systems. Accurate assessment of soil health is critical as a recent study by Tsiafouli et al. (2015) demonstrated that cropping and tillage intensification decreased soil food web diversity with consequences on ecosystem functioning, and this effect was similarly manifested across numerous climatic regions. While a complete transition from intensive tillage to no-till may not be readily practical for vegetable cropping systems, the frequency, depth, and timing of tillage operations could potentially be modified to minimize negative effects on soil health indices.

Putting the Pieces Together: Additive and Synergistic Effects

Although our aggregate meta-analysis (**Figure 3**) illustrated that components of alternative management practices generally improved soil health, characterizing the additive or synergistic effect of combining different alternative management practices is challenging and much more complex. Few studies directly evaluated the combination of these practices let alone reported on the response to soil physical, chemical, and biological indicators of soil health. In general, for this literature review, indices of soil health improved by incorporating amendments, integrating cover cropping and reducing tillage in intensive vegetable agricultural management. However, the meta-analysis does not capture whether there are additive or synergistic impacts on soil health indices when multiple alternative management practices are implemented.

In combining alternative management practices, one study that focused on Hawaii zucchini production evaluated the combination of sunhemp cover cropping and vermi-compost tea amendments, and found improved nitrogen supply, supression of parasitic nematodes, and enhanced bacterivorous nematodes (Wang et al., 2014). In Michigan, the addition of compost and rye cover cropping in a tomato production system did not affect nematode populations, but increased soil microbial biomass, respiration and crop yields (Nair and Ngouajio, 2012). In a 3-year on-farm comparison of conventional vs. alternate farming systems that included both compost amendments and cover cropping in the San Joaquin Valley of California, increased soil carbon contents were observed (Andrews et al., 2002). Even with disparate amendments and cover crop species (Andrews et al., 2002), the combination of these two alternative management practices resulted in general improvements for soil carbon concentration (9.9 vs. 8 g kg^{-1}), soil nitrogen concentration (0.83 vs. 0.70 g kg^{-1}), microbial biomass carbon (256 vs. 192 mg kg^{-1}), bulk density (1.27 vs. 1.30 g cm^{-3}), and water stable aggregates (83.1 vs. 82.8 %).

Research in Salinas Valley, California determined that both soil carbon and microbial biomass carbon increased with yard-waste compost amendments and cover cropping in a vegetable crop rotation on a sandy soil (Brennan and Acosta-Martinez, 2017). But, cover cropping had a greater influence than the amendment on the soil food web; therefore, the authors recommended that farmers in the region should focus more on cover cropping than compost additions to improve soil health (Brennan and Acosta-Martinez, 2017). Other research in Salinas Valley reported on the potential of nematodes to be an integrative indicator of soil health because soils with cover crop treatments resulted in a greater variety of nematode types without impacting crop yields (Ferris et al., 2012). Further research demonstrated that compost amendments combined with cover cropping treatments had a subtle increase or no effect on soil phosphorus dynamics, possibly due to relatively high background levels of soil phosphorous (Maltais-Landry et al., 2015). However, when poultry litter compost was applied to the soil as a nitrogen fertilizer (without a cover crop), it resulted in even higher phosphorus levels that were considered excessive (Maltais-Landry et al., 2015). Therefore, investigating the use of cover crops for not only phosphorus mobilization but also as catch crops has been suggested (Maltais-Landry et al., 2016).

Three publications in our literature database investigated the integration of tillage systems and amendment treatments; one on a sandy loam in Belgium (Willekens et al., 2014) and the others on a silt loam in Illinois (Ugarte and Wander, 2013; Ugarte et al., 2013). Soil biological health indices sometimes

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improved following the transition to alternative management (reduced tillage); however, there were no observed differences in soil physical or chemical attributes among organic amendment or disturbance treatments (Ugarte and Wander, 2013). A soil biological indicator, nematode composition was found to change seasonally but also with management history where communities were more abundant in the less disturbed treatments (Ugarte et al., 2013). In Belgium, both the addition of compost and reduced tillage increased surface soil carbon concentration and soil microbial bacteria and fungi concentrations without affecting crop yields, but the reduced tillage system was considered more important than the compost amendments for its ability to improve soil health indices (Willekens et al., 2014).

In our literature review, only two trials included all four components of alternative management practices as part of their research. First, in southern Uruguay, on small holding farms with silt clay loam soils or clay soils, a multi-year study was undertaken to investigate adapting multiple alternative management practices to individual farm issues (Alliaume et al., 2013). Initial measurements from this study reported that 20-years of intensive vegetable production decreased the proportion of soil aggregates, available water content and soil carbon compared to a paired undisturbed reference soil (Alliaume et al., 2013). Shifting management practices (which included decreasing crop area, changing field slope, additions of green manure, or changes to crop rotations) increased both labor productivity (Dogliotti et al., 2014) and vegetable yield, while also improving soil health through increased soil carbon concentrations (Alliaume et al., 2013). On a sandy loam trial in Denmark, alternative management options were also being investigated for reducing inputs while improving nutrient cycling and pest management through the use of organic matter amendments, cover crops and reduced tillage (Thorup-Kristensen et al., 2012). In their study, vegetable yields were not impacted and there were no significant differences in pests or diseases among organic and conventional management practices; however, the use of fertility building cover crops, rather than the addition of amendments, were found to improve the soil nutrient balances (Thorup-Kristensen et al., 2012).

Theoretical Framework for Integrating Alternative Management Practices

Based on the relative influence that each alternative management practice had on various aspects of soil health (**Figures 2**, **3**) and the literature review of the synergistic or additive effects described herein, we provide a decision framework for farmers and policy makers to consider when adopting alternative management practices: (i) crop rotation (ii) soil amendments (iii) cover crops, and (iv) reduced tillage (**Figure 4**). Crop rotation forms the basis, while organic amendments appear to be the first key to improving soil physical, chemical, and biological health indices. Cover crops offer additional benefits such as weed suppression, mitigating nitrate loss, or countering excessive levels of nutrients from soil amendments. Reduced tillage shows some promise in improving soil health, but may be considered after amendments and cover crops due to lack of research or lack of viable tillage alternatives. As illustrated by our conceptual model (**Figure 4**), we hypothesize that the greatest improvements in soil functioning under intensive vegetable production can be achieved by systematically combining different alternative management practices. In other words, the more pieces of this management puzzle are put together, the greater the corresponding improvement in soil health may ensue (**Figure 4**). In contrast to strictly implementing organic agriculture practices that limit the amounts and types of external inputs—thereby risking yield reductions (Seufert et al., 2012)—this blended approach may reduce the reliance on external inputs (e.g., fertilization, irrigation, herbicides, and pesticides) to maintain or improve both soil health and crop yields in intensive vegetable cropping systems.

The incorporation of alternative practices into conventional vegetable cropping systems may be viewed as a melding between organic and conventional ideologies, and it may represent a direction toward increasing soil health indices without compromising productivity in intensive cropping systems. Organic agricultural principles typically consider environmental factors such as biodiversity, integration, natural plant nutrition and pest management, etc. and often include amendments, green manure, or cover cropping, or reduced forms of tillage—practices that were historically alternative to conventional practices. However, future sustainable food production may not be classified as wholly organic or conventional, but rather a combination of both ideologies. Our results provide a clear example of how alternative practices (that may seem organic-based in nature) might be positively integrated into conventional cropping systems to improve soil health indices, and possibly contribute toward improving the sustainability of intensive food production.

Knowledge Gaps and Limitations

Our meta-analysis was limited based on the results from other published research. This constraint yielded an uneven distribution of crop types. The frequency of certain vegetable crop types that were studied in published literature (**Figure 1**) may have reflected market trends, and/or implies that research on soil health research may be particularly urgent for crop types that tend to have a high nutrient (and fertilizer) demand (i.e., solanaceous, cole, corn, and cucurbit crop typically require 120 to $>$ 200 kg N ha^{-1}), thereby emphasizing the importance of researching soil nutrient reservoirs as an aspect of soil health.

A number of research gaps appeared as a consequence of this literature review. There is a notable absence of long-term studies (10–20-years); while this is understandable due to the elevated logistical and monetary resources that are needed to fund long-term research, maintaining long-term trials in vegetable production will improve the scientific capacity to measure differences in soil health indices. Because long periods are often required before changes in soil can be detected, the knowledge and understanding of ecology, soil science, and plant science has benefited from a number of long-term ecological research (LTER) trials (Hobbie et al.,

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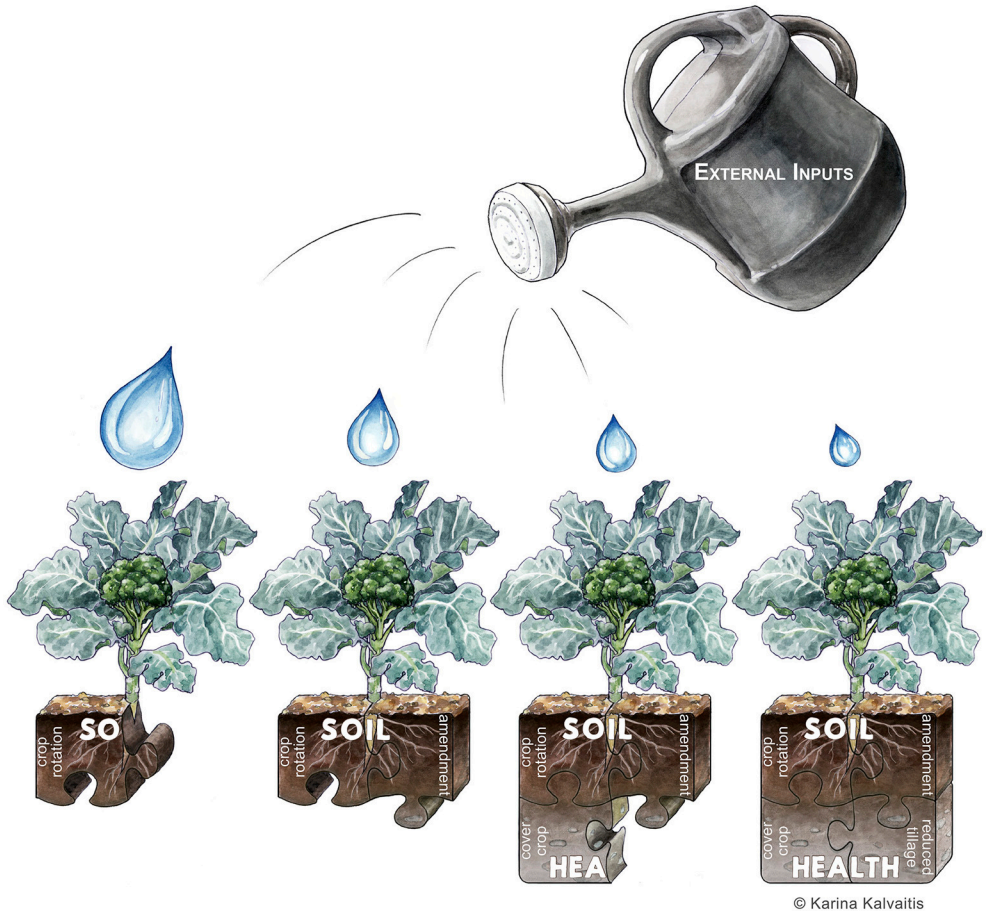

FIGURE 4 | Conceptual model toward improved soil health in intensive vegetable cropping systems. Published with permission from artist.

2009). In the field of agriculture, LTER has mainly focused on field cropping systems; long-term trials focused on vegetable cropping systems are lacking. This limits our ability to accurately project how management and climate change may influence food production and soil health indices in the long run.

Results from studies on intercropping were also notably absent in the literature review. Intercropping, or polycropping, could be an important component to soil health in vegetable cropping systems due to the low-acreage and intensive nature of vegetable production; this warrants future research. Determining viable modifications or alternate tillage approaches for specific vegetable systems remains a conspicuous research gap and will require extensive further research.

Another notable research gap is the limited knowledge on the magnitude of greenhouse gas emissions in vegetable cropping systems. Linking soil health indices or management to greenhouse gas emissions in vegetable cropping systems is needed to better understand the contribution of vegetable crops to global greenhouse gas inventories, and to develop improved strategies for mitigating emissions in intensive cropping systems. Further, endeavors to characterize soil health indices at the molecular level, like organic matter composition, are limited. An improved understanding of stable soil organic matter formation, soil organic matter accumulation and loss is needed to develop improved soil conservation strategies for intensive vegetable cropping systems.

CONCLUSIONS

Vegetable cropping systems are inherently intensive by nature and therefore present considerable concern for soil degradation and crop resiliency. Previous research has demonstrated a dilemma for this type of nutrient-demanding cropping system: while implementing organic management is a convincing option for improving soil health, organic management significantly risks vegetable crop yield reductions due to restrictions on the amounts and types of external inputs. Instead of continuing the ideologically disparate "organic vs. conventional" argument, we evaluated the influence of "alternative" management options that included soil amendments, cover cropping, and reduced tillage—practices that resemble organic or conservation agriculture but without imposing external input limitations—as compared to

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conventional management on soil health indices and crop production in intensive vegetable production. Via a systematic review, alternative management practices generally improved physical, chemical, and biological aspects of soil health without negatively affecting vegetable crop yields, as compared to conventional management. Soil amendments tended to improve soil physical, chemical, and biological properties to the greatest extent; while the incorporation of cover crops reduced nitrate leaching, increased soil carbon levels, and weed suppression. It is evident that reduced tillage systems remain a challenge for vegetable crop production. Our results indicate that future sustainable vegetable cropping systems may embody a blend of management ideologies (i.e., organic and conventional) in order to best maintain or improve soil ecosystem functioning without negatively impacting crop productivity. While we hypothesize that multiple alternative management practices may have an additive or synergistic effect on soil health and crop productivity (**Figure 4**), more research is needed to better characterize the complex interactions among alternative management practices and their influence on vegetable cropping systems. Researchers are encouraged to consider this relatively understudied sub-field of agriculture to contribute to the development of sustainable food production; and researchers and growers alike are urged to focus on management practices that build soil health and simultaneous reduce the reliance on external inputs in vegetable cropping systems.

AUTHOR CONTRIBUTIONS

KC conceptualized the review, secured the funding, collected the literature, and co-wrote the paper. CN conducted the analyses, helped in collecting literature, made the figures, and co-wrote the paper.

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