Journal of Soils and Sediments
https://doi.org/10.1007/s11368-018-1916-4

HUMIC SUBSTANCES IN THE ENVIRONMENT

Humic products in agriculture: potential benefits and research challenges—a review

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Received: 4 October 2017 / Accepted: 5 January 2018

Abstract
Humic products have been used in cropland agriculture for several decades, but lack of widespread credibility has restricted their use to small proportions of farmers. To improve the credibility of humic products, we identify four knowledge gaps and propose pathways of future action to close these gaps. First, while the capacity of humic products to improve plant growth has been proven in greenhouse and growth chambers, more such work is needed in field conditions, especially to determine the modifying effects on humic product efficacy of environmental and management factors, including crop type, annual weather patterns, soil type, and fertility management. Many of the published field studies fail to address any of these factors. Second, full acceptance of humic products by the research community may first require a mechanistic explanation for plant responses to humic products. Some research groups are exploring plant-based mechanisms, but almost entirely in controlled conditions, not in field conditions. Industry often attributes yield responses to enhancement of soil nutrient availability without citing adequate evidence. Microbial-based explanations are also possible. Third, consumer trust in available humic products would be strengthened through industry-wide measures for quality control of humic product production and sale, including standard procedures for measuring their humic and fulvic acid contents and rapid bio-assays for distinguishing effective products from inert frauds. Finally, humic products are widely presumed to promote root growth, which offers the potential to increase soil C inputs and thereby improve soil health. Yet virtually, no such evidence has been presented, in part due to the absence of long-term field trials. Humic product companies in North America have organized a trade association to promote a more knowledge-based industry. To acquire a database that will support these objectives, we propose establishment of a global network of field sites that would measure crop responses to humic products across ranges of humic products, crop types, soil types, and climates. Plant and soil samples would be analyzed by cooperating specialists in advanced laboratories to identify mechanistic processes and benefits to both plant production and soil health. We believe the industry will indeed become more knowledge-based and the credibility of humic products will improve as (i) we learn more about their field efficacy across ranges of field conditions for improving crop yield and soil health, (ii) we gain further insights into possible mechanistic explanations, and (iii) the consumer gains the ability to discern genuine products from fraudulent materials.

Keywords Crop yield · Environmental stresses · Humic products · Standard methods

1 Introduction

Humic products have been commercially available for several decades and have been applied to modest proportions of production fields to increase crop growth and economic yield. Market research reports generally predict ongoing growth for biostimulants in general and humic acids specifically in coming years, driven in part by the desire to make more efficient use of mineral fertilizers in face of increasing costs.

Responsible editor: Jerzy Weber

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We have also noted increased discussion among agribusiness concerns of humic product performance. Yet their validity and general reliability have remained in question, drawing criticism from the research community and government agencies for a lack of factual basis and discouraging their use by mainstream farmers.

Numerous studies have demonstrated significant crop responses to humic products. Rose et al. (2014) found that the best documented studies were conducted under controlled conditions—greenhouses and growth chambers. These studies showed significant responses of in-season plant growth to humic products made from a variety of source materials, although the plants were not grown to maturity. Chen and Aviad (1990) reviewed several types of positive plant responses to humic substances in controlled conditions. Calvo et al. (2014) and Canellas et al. (2015) also indicated generally favorable plant responses to humic products in mixes of controlled and field studies. Visser (1986) listed 33 studies on 30 agricultural crops and other plants that found positive effects of humic materials on plant biomass, yield, or root growth without specifying whether they were conducted in field or controlled conditions. In recent years, additional field studies have appeared from a number of nations, especially the semi-arid and arid landscapes of Egypt (Selim et al. 2009a, b; Selim and Mosa 2012), Iran (Mohammedpourkhaneghah et al. 2012), Saudi Arabia (Daur and Bakhashwain 2013), and Turkey (Turgay et al. 2011). Negative results (Feibert et al. 2003; Hartz and Bottoms 2010; Ahmad et al. 2014; NCR-103 Committee) must also be acknowledged, though, as they also provide information about field efficacy and methodological issues of studying humic products in field conditions.

As collaborating researchers and vendors of humic products, we have jointly observed statistically significant increases in grain yield of maize (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) with humic product application in the US Corn Belt, on some of the most fertile soils in the USA (Olk et al. 2013). Hence, we postulate that humic products can play meaningful roles in mainstream crop production. Toward that goal, we provide here a current assessment of the humic product industry. Our focus will be on four key knowledge gaps that have inhibited growth of the humic product industry. Closing these knowledge gaps would add considerable support to the credibility and value of humic products.

This review is limited to humic product use in cropland agriculture. Humic products can also be used as animal feed supplements, in cosmetics, in the nanotechnology and oil industries, and are occasionally offered as a human health product. These uses will not be addressed here, due to a paucity of peer-reviewed publications.

2 Key knowledge gaps

2.1 Spatial and temporal variability in field efficacy of humic products

2.1.1 Significance

All agricultural inputs vary over time and space in their promotion of plant growth due to multiple factors, including crop type, annual weather pattern, landscape position, soil type, and tillage. Interest in defining these spatial and temporal variabilities to maximize input use efficiency while minimizing environmental pollution (Schepers and Mosier 1991; Randall et al. 1997; Power et al. 2000; Dinnes et al. 2002; Jaynes et al. 2004) led to the science of precision farming (Robert 2002), which has had tremendous impact. Precision farming has become the focus of an ongoing series of conferences and multiple journals, and it has introduced new generations of applicators and satellite links to enable variable applications. As specific examples, copious research has continued for decades into the variance across time and space of crop responses to each mineral nutrient, with special emphasis on N (Wollenhaupt et al. 1994; Parkin 1987; Cassman 1999; Ferguson et al. 2002; Scharf et al. 2005; Jaynes et al. 2011). Pesticide activity is known to be modified by soil properties, including soil C content and clay content (Farenhorst 2006). Crop type is of obvious and paramount importance in determining optimal application rates of fertilizers, pesticides, and all other inputs.

2.1.2 Current state of knowledge

Published studies of humic product efficacy addressed only a limited array of environmental conditions. Many were conducted in controlled conditions, with generally optimal temperature, light, and moisture conditions. These studies are well suited for process-level investigations of humic product effects on plant physiology and biochemistry, but they do not begin to reproduce the wide range of environmental and management conditions found in production fields that may well alter product efficacy. There has been little scientific discussion of how these environmental and management factors alter humic product efficacy. We are unaware of any published database on crop responses to humic products under two or more of these factors simultaneously in field conditions. Khristeva and Manoilova (1950) and Khristeva (1953) grouped crops into four levels of responsiveness to humic materials, and Verlinden et al. (2009) compared the responses of four crops to one humic product in six field studies conducted in 2006 in Flanders (Belgium). Seyedbagheri (2010) measured potato response to one humic product experiment at four sites in different years, and El-Mesker et al. (2014) studied maize response on two soil types in 2 years. Several other field studies varied one or two environmental or management parameters, often the application rate of fertilizer (Azarpour et al. 2012; Moraditochaee 2012; Selim and Mosa 2012; Sanli et al. 2013; Zhang et al. 2013; Nazli et al. 2014; Vanitha and Mohandass 2014; Zaki et al. 2014) or of humic product (Brownell et al. 1987; Fernandez-Escobar et al. 1996; Feibert et al. 2003; Albayrak and Camas 2005; Selim et al. 2009b; Saruhan et al. 2011; Sajid et al. 2012; Selim et al. 2012; Sanli et al. 2013) or of both (Ece et al. 2007; El-Shabrawy et al. 2010; Mahmoud and Hafez 2010; Rizk et al. 2013; Saha et al. 2013; Ahmad et al. 2014), but to our knowledge, no other study included more than two sites or 2 years. A few studies evaluated humic products applied to dryland crops in times of moisture stress (Xudan 1986; Khan et al. 2010; Shahryari et al. 2012). To our knowledge, only two studies examined crop response to humic products applied with discrete levels of moisture stress imposed through decreased irrigation rates (Ismail et al. 2007; Almarshadi and Ismail 2014), no study has compared humic product performance between conventional tillage and to no-tillage, and none has compared crop response to the same product on multiple soil types.

In addition to environmental and crop variability, humic products can vary among themselves in their promotion of crop growth, certainly by crop type and possibly by other environmental or management parameters. Such variability can be expected, given the range of source ores used, modes of extraction, and post-extraction modifications that are currently practiced. Yet we are unaware of any publication that has compared the benefits of multiple products in the same research trials.

2.1.3 Call for future action

Each of the environmental and management factors listed above will likely alter humic product efficacy, to an extent that will depend on its local interactions with other environmental and management conditions. Hence, there is an immense matrix of potential combinations of these factors of amendment efficacy. Moreover, as product efficacy will likely vary through interaction with these factors, we expect the optimal application rate of the product to vary as well. It is impractical to determine the efficacy of each humic product in every possible combination of environmental and management conditions, but there is the need for more detailed information than the current situation of a very few blanket application rates for multiple crops in all possible environments and managements. The next step should be multi-year and multi-location studies that maintain treatments and uniform sampling procedures and analyses across years, in order to determine the consistency of humic product effects across different soil types and annual weather patterns, especially precipitation level, and ultimately to develop the ability to identify optimal site-specific application rates. The crop rotations that are characteristic of each local region could be maintained throughout each study to determine responses of multiple crops under the same conditions. As humic products gain further attention, additional field trials will likely arise for a wider array of crops and also for multiple humic products. Informed adjustment of application rates to local conditions would avoid problems with (i) limited crop response due to under-application, (ii) situations where products cannot improve crop growth, and (iii) wasteful over-application, which anecdotal evidence indicates can also lead to toxicity-like inhibition of crop growth.

2.2 Mechanistic explanations of humic product effects

2.2.1 Significance

A mechanistic understanding of plant responses to humic products would improve the prediction of when and where crop production would benefit from humic products and their interactions with other crop inputs. It would enable development of better products. It would also help convince the research community of the viability of humic products, which may in turn attract more favorable interest from other sectors of the agricultural community, including crop consultants and government regulators.

2.2.2 Current state of knowledge

The most commonly proposed explanations can be grouped into themes of soil nutrient availability, other soil properties, direct plant biostimulation, and microbial processes. Humic product vendors describe any of several improved soil properties as possible causes for crop yield responses to their products, especially nutrient availability. Their selection of soil properties is based on known benefits of soil organic matter. Yet such improvements are unlikely to occur merely through use of liquid humic products, given the miniscule amounts of organic matter added to soil via recommended application rates of liquid humic products (often less than 1 kg organic matter ha^{-1}) compared to the tens of thousands of kg ha^{-1} of native humus already found in the soil. Claims of increased nutrient availability are based on greater crop nutrient uptake per hectare, but this outcome is more likely driven by enhanced plant growth—greater demand for nutrient uptake is the driving force instead of greater nutrient availability. Increased uptake is claimed for several nutrients, whose availabilities are controlled by diverse soil factors, including microbial transformations (N), pH and diffusion rates (P, Fe, Mn), and chemical interactions with soil minerals (K) to name a few. It is unlikely that all these processes would be favorably influenced by one amendment, especially at very low application rates.

Researchers, in contrast, have largely focused on plant-based mechanisms for stimulating growth, as reviewed by Khristeva (1968), Visser (1986), Nardi et al. (2002), Zandonadi et al. (2013), Berbara and Garcia (2014), and Calvo et al. (2014). Multiple plant processes have been affected by humic substances in general, including enzyme activity, protein metabolism, photosynthesis, respiration, and uptake of water and nutrients, and the underlying mechanisms have long been conjectured to involve hormone fluxes, the hydroxyproline:proline ratio, cell membrane permeability, electron chain transport components, free radical activity within the humic structure, and reactive oxygen species in plants (Vaughan and Malcolm 1985; Vaughan et al. 1985; Vaughan 1986; Visser 1986; Berbara and Garcia 2014; Calvo et al. 2014). More recent research has addressed activity of the H^+-ATPase enzyme (Zandonadi et al. 2013; Calvo et al. 2014; Canellas and Olivares 2014), which is located in the cell membrane and pumps protons out of the cell, creating an electrochemical gradient across the membrane that can be exploited by other membrane-bound transporters to import essential nutrients, which in turn attract water. Under controlled conditions, these effects are associated with beneficial changes in plant hormone fluxes (Mora et al. 2010). The expected changes in plant growth that should result from these hormone fluxes are consistent with our field observations of maize growth responses to humic products. Plant genetic expression has shown responses to humic materials (Canellas and Olivares 2014; Calvo et al. 2014). Some arguments exist for increased Fe availability as the underlying cause (Chen et al. 2004; Aguirre et al. 2009). Limited effort has been directed at possible roles of microorganisms in plant responses, whether they are located in the soil, rhizosphere, or plant. In total, plant responses indicate humic products affect fundamental levels of plant metabolism. These analyses have been conducted on plants grown under controlled conditions, though, which do not replicate the variable conditions and multiple stresses that routinely impact crop growth in field conditions. Published reviews of these studies have not discussed whether the variable results reflect the multitude of products and natural humic substances used in these studies.

2.2.3 Call for future action

The process-level causes of plant responses to humic materials should be identified if humic products are to be accepted by the research community and those agricultural sectors that look to researchers for leadership—extension workers, crop consultants, government agencies, and progressive farmers. Industry representatives have shown varying levels of interest in determining these mechanisms; it is possible to demonstrate the usefulness of a product without fully understanding its molecular actions.

Nevertheless, we call for increased collaboration between researchers and industry to develop a better understanding of the underlying mechanisms, and with greater emphasis on field conditions. Currently, researchers are identifying mechanisms of plant responses under controlled conditions, where the plants encounter little if any environmental stress. Yet stress alleviation has been conjectured as a primary means through which humic products best express their benefits to plant growth (Zandonadi et al. 2013; Calvo et al. 2014). Similarly, Savvides et al. (2016) postulated that plants can respond against multiple environmental stresses through stimulation by suitable compounds, without specifically citing humic molecules. Our field observations have shown that humic products enhanced plant response against stresses arising from drought or dense population stands. In fact, these stress alleviations were the primary mode for grain yield response: in our field trials that had little or no stress, humic products had much less impact on crop economic yield. Elsewhere, humic products induced greater plant resistance to saline soil conditions (Aşik et al. 2009; Aydin et al. 2012), and anecdotal evidence exists for enhanced plant tolerance to cold and to uptake of heavy metals. Each of these tolerances likely involves different physiological pathways and different plant growth regulator compounds than do the others. The capacity of humic products to invoke one of these responses that fits a particular situation must require a fundamental cellular mechanism that can manifest itself in different forms depending on local conditions. Ultimately, an amended plant is proving more capable to mitigate whichever stresses it encounters. Potted plants in controlled conditions do not experience the range of stresses and the associated effects on plant processes that occur in field condition. Therefore, we call for more process-level research to be conducted on plants grown in field conditions so that the full benefits of humic products can be documented and so that plant processes triggered in response to field stresses and their modification by humic products can be observed and explained. The field setting would also determine the significance that the agricultural community can attach to plant processes observed under controlled conditions.

This situation similarly describes the search for the compound(s) in humic products that provoke crop responses. The research community and its associates seek identification of the active compound(s) before they will fully accept humic products, while industry has shown mixed interest in the search. Identification of the causal compound(s) could enable both more effective products and better prediction of which crops and field settings are most suitable for humic products. Yet this search promises to be yet more difficult than the identification of the plant processes underlying crop responses. A promising start for identifying causal compounds would seem to determine which humic fractions have greater biological activity and then compare their respective chemical compositions. Smaller molecular weight compounds would seem likely to have greater mobility and thus more biological activity, yet they have not been clearly shown to better stimulate plant growth than do larger molecule sizes, as reviewed by Zandonadi et al. (2013). Sleighter et al. (2015) found that the more hydrophilic fraction of a humic product better stimulated maize shoot growth in a greenhouse pot study, but the more hydrophobic fraction better stimulated root growth. Humic products could prove to have multiple modes of biological activity, and the causal compounds could be one or multiple in number, or they could in fact be 3-dimensional configurations of nearby functional groups. Must all humic products have the same causal compounds whether they are derived from millions-year-old leonardites, thousands-years-old peats, or instead months-old composts? Formidable challenges loom in the search for causality.

In-season measurements of crop growth at key growth stages would illuminate how the yield response to humic products develops and expresses itself through yield components. Such intense measurements are needed for both determinate and indeterminate types of crops, given the significant differences in their growth and development patterns. Geographic information systems can be used to quantify soil and weather effects on product efficacy. The search for mechanistic explanations also needs to accommodate those studies that found no benefit of humic product to crop growth, as these studies will help identify the conditions that limit potential benefits.

2.3 Industry-wide standards for humic product quality

2.3.1 Significance

Consumer confidence in commercial products is supported when broadly accepted procedures exist for providing quality scores. Perhaps the two most useful quality tests for a humic product would be (i) the quantities of humic acid material and fulvic acid material in a product and (ii) biological activity.

2.3.2 Current state of knowledge

The humic product market lacks universally recognized standard procedures for measuring either the humic acid/fulvic acid contents or the biological activity of humic products. Consequently, the consumer cannot ascertain for any product its concentration, source material, or variability among production batches. The consumer cannot discern effective products from molasses, lignosulphonates, or hard coal—similarly appearing but much less expensive substances that are rumored to be sold as humic products and are of uncertain or negligible value to crop production.

Official procedures for measuring humic acid and fulvic acid contents are sometimes designated by national governments. Varied approaches are apparent. China postulates multiple standard methods, depending on the chemical form and intended use of the humic product. Russia also uses multiple standard methods, depending on the source material of the humic product. Additional methods are used in other countries, sometimes as an official procedure and sometimes as a widely used method without formal designation (Table 1). Several of these procedures do not attempt to measure fulvic acids, many but not all attempt to separate the much denser inorganic contaminants (soil and sediment) that can interlace with the source ores, and until recently, none has attempted to discern adulterants or fraudulent materials.

On behalf of the Humic Products Trade Association (HPTA), a North American-based industry group (http://www.humictrade.org/), Lamar et al. (2014) developed a procedure with the intention to meet all these objectives. Its extraction of the humic acid and fulvic acid fractions from a humic product or source ore uses alkaline extraction, as do most other procedures. A key difference is that inorganic contaminants (soil, clays, sediments) in the humic acid fraction are measured through high-temperature combustion of the extracted fractions and subtracted from the total humic acid mass to estimate the mass of organic humic acids. Following the conventional acidification of the NaOH extract to precipitate humic acids from the more soluble fulvic acids, the HPTA procedure separates potential fraudulent materials that are carbohydrates (e.g., molasses) by passing the fulvic acid supernatant through a DAX-8 resin column that adsorbs relatively hydrophobic fulvic acid molecules for later elution and collection, while letting carbohydrates and other hydrophilic molecules pass through for disposal. It does not distinguish lignosulphonates from the hydrophobic fulvic acid fraction. Instead, this distinction would be accomplished through Fourier-transform infrared spectroscopy and/or measurement for high S concentration. Use of the resin column adds cost and labor to the procedure, and it necessarily provides lower estimates of fulvic acid concentrations than do other analyses for fulvic acid concentration that forego resin column use to combine both hydrophilic and hydrophobic molecules together with any carbohydrates. For example, we had three samples of a humic product analyzed in a commercial laboratory by both the HPTA method and the method of the California Department of Food and Agriculture (CDFA). The HPTA method was found to give lower estimates for both the humic acid fraction (by as much as 30%) and the fulvic acid fraction (by as much as 25%) compared to the CDFA procedure. Adoption of the HPTA method remains an ongoing process. Although its lower estimates of humic acid and fulvic acid concentrations are intended to more truthfully depict concentrations for a commercial product or source ore, they may discourage purchase of those materials compared to other products or ores that claim higher humic and fulvic contents based on a different procedure that fails to discern carbohydrates, inorganic contaminants, or other adulterants.

Table 1 Selected procedures for measuring humic acid (HA) and fulvic acid (FA) concentrations of commercial products and their source ores

Method	Extractant	Mode of measuring HA	Separation/removal of inorganics?	Separates and measures FA?	Uses resin column to measure FA?
Italy official method[a]	0.1 M NaOH/0.1 M $Na_4P_2O_7 \cdot 10\ H_2O$	Dissolved organic C ($K_2Cr_2O_7$ oxidation)	Yes	Optional	Yes
Spain official method[b]	0.1 M NaOH/0.1 M $Na_4P_2O_7 \cdot 10\ H_2O$	Dissolved organic C ($K_2Cr_2O_7$ oxidation)	Yes	Could be calculated as difference between total extractable C and humic acid-C	No
Mehlich-based colorimetric[c]	0.2 M NaOH/0.002 M diethylene-triamine penta acetic acid/2% ethanol	Visible light absorption at 650 nm, calibrated against commercial humic acid	No	No	No
CDFA[d]	1.0 M NaOH	Oven-dried mass	No	No	No
International Humic Substances Society (IHSS)[e]	0.1 M NaOH	Freeze-dried mass	Yes	Yes	Yes
IHSS-semi-automated[f]	0.1 M NaOH	Dissolved organic C (mechanized)	Yes	Yes	Yes
Humic Products Trade Association[g]	0.1 M NaOH	Oven-dried mass	Yes	Yes	Yes

[a] Official Gazette of the Italian Republic (2001)

[b] Spanish Official State Gazette (1991)

[c] Lamar and Talbot (2009)

[d] California Department of Food and Agriculture (1996)

[e] Swift (1996)

[f] Van Zomeren and Comans (2007)

[g] Lamar et al. (2014)

No method has been proposed as a standard procedure for measuring the biological efficacy of humic products. Several rapid bioassays have been reported in the literature to test bioactivity, including seed germination, root elongation, and young shoot growth rate (Chen and Aviad 1990), H^+-ATPase activity and H^+ pumping (Canellas et al. 2002), and biomass and cell numbers of algae, bacteria, fungi, and yeast (Vaughan and Malcolm 1985). Any single rapid bioassay is by itself unlikely to quantitatively reproduce the capacity of each humic product to promote growth for each of the many crops grown globally in diverse settings. It must also be adaptable to the ranges of humic ores, humic acid products, and fulvic acid subfractions that can be marketed.

2.3.3 Call for future action

Ideally, one procedure would accurately and precisely measure concentrations both of humic acids and fulvic acids in commercial products as well as their source ores. Further, it would distinguish humic materials from inorganic contaminants, organic adulterants, and fraudulent materials, while providing reproducible results when performed by different laboratories. The affordable cost of this procedure will be defined by its designated use—annual testing of products for registration purposes can involve a more expensive procedure than would a rapid test intended for in-house quality control checks of individual batches during production of humic products. We propose further dialog among proponents of the methods currently used, together with industry and government regulators to identify the optimal method: what is the balance between affordability versus accuracy, precision, and capability for discerning fraudulent materials such that the method will be regularly used and thereby support a knowledge-based industry? The discussion should also establish a plan for regular implementation of the method. Its primary objective may well prove to merely be the distinction of genuine humic materials from adulterants or fraudulent materials, instead of quantifying slight differences among genuine products in their humic acid or fulvic acid concentrations.

Field efficacy of a product may prove to be more a function of the as yet unidentified chemical constituent(s) that promote plant growth than concentrations of the operationally defined humic acid or fulvic acid fractions. The ideal bio-assay would measure the concentration of the growth promoter compound(s), which to date remain unidentified. In the meantime, if no single bio-assay can reproduce all humic product effects on crops globally, then we propose identification of a short list of useful bioassays, each of which could capture complementary aspects of plant growth. Products would undergo voluntary assessment by this short list of bioassays, and product labels would then list either the bioassay results or a website where this information is found.

2.4 Benefits to soil health

2.4.1 Significance

In recent years, soil health has received increasing interest, as funding has increased in this area. Assays to define soil health are being presented and discussed by the newly formed Soil Health Institute (http://soilhealthinstitute.org/). Key assays involve soil C and N accumulation and mineralization, physical properties, and parameters of microbial activity. Increasing research efforts are directed at determining crop management practices that can improve soil health in economically viable manners. Some practices are already known to promote soil health, but they involve additional costs, labor, or training beyond conventional practices, for example cover crops, manure applications, and no-tillage.

2.4.2 Current state of knowledge

As described above, recommended application rates of liquid humic products are so low that their organic matter content is inadequate to increase soil C stocks. However, humic products might improve soil health through increased root growth. This benefit is commonly viewed by the humic product industry as a reliable crop response to product application, and it has been reported in some published papers (Lee and Bartlett 1976; Chen and Aviad 1990; Canellas et al. 2002). If this were a general response across crop and soil types, it would constitute a substantially greater C input into the soil than the C content of the products and, hence, a potential agent for improving soil health. Root carbon might be the primary source of stable soil organic matter (Balesdent and Balabane 1996; Gale and Cambardella 2000), perhaps due to its more phenolic or cross-linked chemical nature compared to aboveground stover (Bertrand et al. 2006) or to its imbedded location within the soil matrix (Mendez-Millan et al. 2010). Root exudate input into the soil may well also increase with expanded root growth, and exudates are immediately available nutrition for soil microorganisms, whose activity is pivotal to several soil health measures. Any direct effect of humic product on microbial activity independent of root growth would further benefit soil health. For example, anecdotal reports exist of farmers applying humic products post-harvest in stover-rich fields to accelerate stover decomposition.

Separate from liquid products, ground leonardite ores are also applied at rates as high as 550 kg ha^{-1}. Anecdotal evidence exists for their capacity to improve soil physical properties. For example, a mixture of a solid humic product with annual ryegrass (*Lolium* sp.) was found to accelerate fragmentation of a subsoil fragipan at a rate faster than any other amendment (Murdock 2017), presumably due to accelerated microbial activity. While the C input at these application rates is still dwarfed by total soil C stocks, most soil organic matter is stabilized over the short term, raising the issue whether large rates of solid ore increase the level of available soil C.

Despite the potential of humic products to improve soil health, scant work has addressed this topic in field conditions. A review by Billingham (2012) found that nearly all of the studies on soil physical properties were performed in laboratories and greenhouses, with very few set in field conditions. Gümüs and Şeker (2015) also described a sparse literature on physical properties in field humic studies. Preliminary benefits to dry aggregate stability, penetration resistance, and bulk density in field conditions were reported by Olk et al. (2017).

A major limitation to progress has been the absence of long-term field trials on humic product application. Nearly all published humic product field studies, as well as unpublished in-house studies conducted by humic product vendors, are for only one or two growing seasons, or they change the location each field season. The full benefit of humic product to expanded root growth and in turn soil health would be fully expressed only after several years of continuous application to the same plots or strips.

2.4.3 Call for future action

The potential for humic products to improve soil health in mainstream cropping systems should be evaluated only in long-term field trials. Soil health would preferably be measured simultaneously with crop growth and economic yield, incorporation rates of crop residues, and perhaps even root measurements. Rapidly measurable soil properties include aggregate stability, bulk density, penetration resistance, and water-holding capacity. Other suitable analyses include water infiltration rate, shear and tensile strength of soil cores, and microbial parameters such as microbial biomass, enzyme activity, and C mineralization. Studies should be done with both tillage and no-tillage management systems, with care taken to avoid sampling in zones affected by implement traffic.

3 Global network

We propose establishing a global network of long-term field trials that would document for a wide range of regions, crops, and soil types the effects of humic products on crop growth and economic yield. Through the network, field trial managers would exchange knowledge gained from their trials and share plant and soil samples with selected laboratories offering specialized analyses that would further explore product effects on plant physiological processes, plant structural biochemistry, microbial activity, and soil properties.

The manager of each site would apply the product of their choice, following manufacturer recommendations for rate, timing, and frequency of application. Treatments must be maintained in the same plots each year to enable measurements of long-term soil benefits. Data collection and analysis and field sampling strategies would be standardized across sites to the maximum possible extent. Site managers would document aspects of the local environment (intrinsic soil properties, drainage, nutrient deficiencies, weather patterns) and management practices (tillage, nutrient and pesticide applications, crop genetics, irrigation, humic product application, economic yield level) that could help develop an integrated understanding across sites of the interactions between humic products and the environment. Based on recent field and laboratory results, promising analyses that the collaborating specialized laboratories would perform include plant hormones, root versus shoot lignification, plant carbohydrate accumulation, grain or fruit quality, genetic expression, enzymes, reactive oxygen species and the enzymes that control them, and cell membrane permeability. We speculate that key enzymes for measurement would include the H^+-ATPase, as described above, and starch synthase forms, as greater starch or sugar formation seems to be a common outcome of humic product application. Genes for sucrose metabolism were a primary responder to humic substance addition to maize roots (Carletti et al. 2008), and potato and sugar beet are among the most vigorous responding crops to humic products, while oil crops are among the least responsive (Khristeva and Manoilova 1950; Khristeva 1953). Anecdotal reports exist of increased sugar content of maize and pineapple with product application.

Longer-term continuation of the field trials would enable (i) evaluation of product efficacy for crop economic yield under different weather patterns, (ii) monitoring of evolving soil health properties, and (iii) elucidation of the spatial and temporal variability in crop responses to humic products that may allow for the development of precision application methods similar to those for other crop inputs (e.g., lime and NPK). Cooperators that have expressed interest in joining this network include humic product companies and researchers who have sites in Brazil, Mexico, Ukraine, Saudi Arabia, and the USA. Additional sites are welcome, as are laboratories that can provide other specialized analyses for humic product effects on the soil-plant system.

4 Conclusions

Humic product use has long been inhibited by limited knowledge of their field efficacy, exaggerated claims from industry, limited understanding of the underlying mechanisms for crop responses, and the inability to discern genuine products from frauds or to assess their bioactivity. With recent initiatives to provide a knowledge-based foundation to the industry, including creation of the Humic Products Trade Association and increasing ties to the International Humic Substances Society, we believe the industry will undergo further growth as it gains credibility among mainstream farmers.

Compliance with ethical standards

Conflict of interest DC Olk and DL Dinnes received research grants from Minerals Technologies, Inc. (JR Scoresby and JW Darlington) and separately from Ag Logic Distributors (CR Callaway), but results from those projects are not presented here.

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