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Soil Biological Fertility: Foundation for the Next Revolution in Agriculture?

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Feeding the world's population in 40 years will require improved efficiency in the use of plant nutrients and enhancement of soil resources. Over the past 60 years, agricultural production has rapidly increased; however, continued degradation of soil may limit further increases. Improving the soil through enhanced soil biological activity has been proposed as a method of increasing the capacity of the soil to produce crops. Ongoing evaluations of one soil biological fertilizer with a patented process to convert and complex manure into stable finished products (AgroBiotic fertilizers) have been conducted in research plots and producer fields and have shown positive effects on grain yield and potato production. These effects are larger in soils with limited biological activity, suggesting that adding this unique AgroBiotic fertilizer helps restore the biological nutrient cycling in the soil. New developments and innovations that improve nutrient availability and the efficacy of soil biological fertilizers have the potential to help restore degraded soils and improve their production efficiency and capacity to feed the world's population.

Keywords AgroBiotic fertilizer, nutrient cycling, soil biological activity

Introduction

Projections of world population reaching nine billion by 2050 create a daunting challenge to agriculture. It has been projected that the same amount of food cumulatively produced over the past 500 years will have to be produced over the next 50 years to meet the nutritional needs of world population (Tilman et al. 2011; Wise 2013). Given the shrinking quantity and quality of land resources and water required to grow food, feed, fiber, and now biofuel, the need to intensify agricultural production is clear.

The remarkable successes of global agriculture have been possible through revolutionary developments and application of science and technology. The industrial revolution brought mechanization to agriculture, thus enabling rapid cultivation and harvest of increasingly larger areas of land. The green revolution produced greater quantity and quality of yields through genetics and breeding coupled with advances of nutrient management. The information revolution has enabled greater precision of spatial and temporal management decisions via sensing, mapping, and variable-rate application technology that are

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reducing input losses and costs via increased production efficiency. The industrial, green, and information revolutions in agriculture were the result of agricultural research (Alston, Beddow, and Pardey 2009). Mechanization, genetics, and information technologies continue to advance to the benefit of producers, consumers, and environmental quality as agricultural research continues to improve world agriculture.

Accelerating land-use changes from agriculture to urban, soil degradation, and shortages of water and nutrients are raising questions as to the ability of the technological advances of the industrial, green, and information revolutions to sustainably meet future demands for food, feed, fiber, and biofuel. The need to intensify production is being augmented by challenges from changing climate: The agricultural revolutions were possible because of a long period of stable climate. This stability appears to be coming to an end, with agriculture production systems facing exposure to increasingly variable temperature and precipitation patterns. The growing intensity of these challenges is such that the evolutionary pace of agricultural research may be insufficient to provide timely solutions, and thus revolutionary advances are urgently needed. Fortunately, there are indications that the expanding frontier of soil biology, and more specifically new approaches to soil biological fertility, may meet this need.

Soil Biological Fertility and Crop Nutrient Supply

Inorganic sources of nutrients for crop growth have been a mainstay of agriculture since the early nineteenth century. The importance of inorganic nutrition for crop production is shown by the 2010 estimate for world consumption of nutrients: 150 million metric tons. Projected crop production by 2030 is expected to increase by more than 50 percent for corn, wheat, and rice (*Orzya sativa* L.) based on FAO projections (Alexandratos and Bruinsma 2012); to produce this level of crops will require a 50 percent increase in the use of nutrients over current levels. These assumptions are based on the quality of soil resources remaining constant with no further degradation. However, projections for degradation of the soil resource are expected to increase on a global basis. The soil degradation process is expected to further destroy the capacity to supply nutrients except for what is supplied through inorganic sources. Degradation of the soil resource will also limit soil water availability, which will limit production in spite of added nutrients (Hatfield 2012).

In a recent overview of soil biological fertility, Abbott and Murphy (2007) provided an analysis of a new paradigm to supply plant nutrients based on unlocking the potential of soil biology. For their review they define soil biological fertility as “the capacity of organisms living in the soil (microorganisms, fauna, and roots) to contribute to the nutritional requirements of plants and foraging animals for productivity, reproduction, and quality (considered in terms of human and animal wellbeing) while maintaining biological processes that contribute positively to the physical and chemical state of the soil” (Abbott and Murphy 2007, p. 4). This definition provides a working model that illustrates the direct relationship between the soil biological system and the supply of nutrients to plants. Perhaps the role of the delivery system for nutrient supply to plants (i.e., soil biology) may provide opportunities to enhance efficient forms and/or accelerate the delivery of crop nutrients.

Soil Biological Activity and Soil Degradation

Soil degradation is extensive worldwide and is increasing in severity because of the continual loss of biological activity within the soil. This was noted by Lal (1993), who postulated that soil degradation is a major threat to agricultural sustainability and environmental quality, especially for the tropics and subtropics. Water erosion is the primary factor causing degradation in tropical highlands (areas above 1000 m above sea level, covering 4.5 million km^2) (Nyssen, Poesen, and Deckers 2009). Conversion of cropland in the Horquin sands of China from pasture created significant changes for crop yield and soil properties (Zhao et al. 2007). The increasing pressure for food, which replaces the traditional practice of 10–15 years of cultivation followed with 10–15 years of fallow with a continuous cropping practice, has increased the rate of soil degradation (Kidron, Karnieli, and Benenson 2010). They found that soil organic matter (SOM) content showed the strongest relationship to soil degradation, and practices that accelerated the removal of SOM increased the rate of degradation.

Biological degradation is associated with the dynamics of the microbial systems within the soil profile. Microbial activity and soil biodiversity are linked with the soil organic carbon (SOC) pools in the soil and are ultimately associated with the depletion of SOC and the turnover rates of the SOC pool. Bastida et al. (2008) proposed a biological index for soil quality and, when comparing different methods for this, found that metabolic quotient (ratio of respiration to microbial biomass) is a potential index for evaluating ecosystem disturbance, or maturity. They proposed that any method incorporating some aspect of soil biological status or function would be a valuable indicator of soil quality or soil degradation. If we follow the hypothesis of Abbott and Murphy (2007), then indicators of soil biological activity are a viable indicator of the state of biological degradation in soils. Haney et al. (2001) showed that a 24-h CO_2 evolution measurement from soil is highly correlated with soil nitrogen (N) mineralized from soils with different amounts of dairy manure. Franzluebbers, Zuberer, and Hons (1995) compared different methods for quantifying soil respiration, N mineralization, and microbial biomass and found that all methods were correlated with one another. However, methods using longer incubation times appeared reliable for estimates of nutrient availability. Recent developments of soil tests by Haney et al. (2001) suggest that it is possible to use shorter incubation times and achieve reliable estimates of N mineralization in soil. The continued refinement of such tests demonstrates potential to use soil tests related to biological activity and thus provide reliable estimates of N mineralization. Perhaps, more importantly, these tests are a direct indication of nutrient availability, with enhanced soil health calculations emphasizing the natural system, which is driven by organic carbon (C) in the presence of water.

If we extend the results from these soil tests we can conclude that soil fertility is directly related to the heterotrophic activity of soil microbes and their role as part of the soil complex (Alef et al. 1988). If this premise is true, then there should be a direct relationship to soil management practices, which foster soil biology and the resultant nutrient supply in the soil. Haney et al. (2012) found that the relationship of water-extractable organic C/N and soil microbial activity provided a more robust measurement of the soil substrate responsible for soil microbial activity. Glaser, Turrión, and Alef (2004) used amino sugars to characterize microbial communities in the soil and found these concentrations were small in microbial biomass compared to the total concentrations in the soil. There were differences in concentrations of amino sugars between bacteria and actinomycete populations. They concluded that evaluation of amino sugar concentrations provides better biomarkers than changes of soil microbial biomass.

There are tests available to measure the biological activity in soil; however, the larger question is what management practices can be implemented to enhance the soil biological system, which in turn promote soil fertility and potentially improved mineral and nutrient content in grain and vegetable products. This has implications for food security in general based on increased productivity and, more specifically, improving the mineral content, nutritional value, and quality of vegetables, grains, other crops, and meat products.

Soil Amendments to Promote Biological Activity

There has been considerable research on the impact of soil amendments on change in soil biological systems. Rogers and Burns (1994) showed that inoculating soils with *Nostoc muscorum* affected both the soil chemical and biological properties, increasing total C by 50–62 percent and total N by 111–120 percent, accompanied by 500-fold increase in soil bacteria. Soil aggregate stability was increased by the addition of the cyanobacteria; however, if the soil was disturbed by tillage, aggregate stability was destroyed. Huang et al. (2013) observed the same response in soils from China in which reduced tillage significantly increased soil microbial activity and total biomass. Perucci (1992) computed a biological index of fertility, and enzyme activity number in soils, which were amended with municipal refuse compost over a 3-year period at rates of 30 and 90 t ha^{-1}, and found that the biological index of fertility did not change after these additions. However, a hydrolyzing coefficient was able to provide an index of good soil fertility because of the relationship of this coefficient to microbial biomass. Burket and Dick (1998) observed that soils from Oregon with similar formation processes differed in their chemical and biological parameters because of the management systems imposed on them. A strong and significant relationship between microbial biomass and N mineralization in these soils was observed. Increases of microbial biomass and N mineralization suggests that management systems directed toward promoting microbial activity can enhance nutrient cycling in soils.

Badalucco et al. (2010) evaluated the effect of changing from intensive to sustainable agricultural practices on a soil from southern Italy (Lithic Haploxeralf) and found increased soil microbial biomass and an increase of soil organic matter (SOM) content because of the reduction in tillage and addition of manure to the soil. The linkage between the addition of organic materials to the soil and reduced tillage on soil microbial biomass suggests that soil management practices limiting the soil disturbance coupled with organic nutrients create a positive response in the soil system (Morvan, Nicolardot, and Péan 2006). Dumontet et al. (2001) observed that tillage had a greater effect than crop rotations on the physical, chemical, and biological properties of a Vertic Ustorthen soil in southern Italy. As the amount of tillage decreased, there was an accompanying increase in soil microbial biomass.

Iovieno et al. (2009) found a similar result for two different Mediterranean soils with differing organic matter and showed that adding compost materials significantly increased the microbial activity of the soil when coupled with reduced tillage with greater microbial activity than present under inorganic fertilizers. They observed that changes in soil microbial activity and soil organic C were cumulative, thus demonstrating the potential value of repeated compost applications. Because many of the reactions occurring in soil are related to enzyme activity, temperature may be a factor affecting the rate of the processes within the soil. Fraser et al. (2013) observed that the supply of C in soil was a larger factor than temperature in their soil; however, this study was constrained to one soil under a grassland condition without the effect of tillage as a variable. Previous studies on tillage comparisons suggest that tillage is affecting the C, temperature, and soil moisture content in the soil, and that these factors are critical to enzyme activity (Zaman et al. 2004). The addition of a combination of organic and inorganic fertilizers stimulated microbial growth, altered the soil microbial community, and increased enzyme activity compared to the use of inorganic fertilizers alone (Lazcano et al. 2013). They found that bacterial growth was stimulated by the fertilizer regime whereas fungal growth responded primarily to the total amount of fertilizer applied. Nutrient supply to the crop and crop yields of sweet corn (*Zea mays* subsp. mays) were maintained with the incorporation of organic fertilizers in the fertilizer regime, suggesting that responses to organic fertilizers occur in the short term.

Harmel and Haney (2013) evaluated their soil-test methodology (Haney and Haney 2010) to compare consequences of no fertilizer, the traditional fertilizer rate, and a reduced fertilizer rate based on the soil-test results on corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), oats (*Avena sativa* L.), and grain sorghum (*Sorghum vulgare* Moench.) across 35 site-years of data and found the reduced N rates derived from the soil test of mineralizable N increased profits and did not decrease crop yields.

These research results point out that soil microbial biomass is directly affected by C availability and reduced tillage. Because soil microbial biomass does exhibit a direct relationship to nutrient cycling within the soil, we can infer that management practices promoting a more stable soil environment of temperature and soil water coupled with the organic C source will promote enhanced soil fertility derived from soil microbial systems. Improved soil biological fertility can be related to a number of observations related to the maintenance of an active biological systems, and because most soil organisms are abundant in the upper soil layers, management practices (e.g., reduced tillage and maintenance of the crop residue) will temper the soil microclimate in this layer to allow the biological system to flourish (Hatfield and Prueger 1996). Soil organic matter is necessary for nutrient cycling and soil aggregation as evidenced by the large number of studies that show positive impacts with the addition of manure, compost, or even organic and inorganic fertilizer combinations. Soil management practices that produce these responses and prevent soil erosion are considered to be cornerstones of sustainable agriculture.

Promising Results with AgroBiotic Fertilizer

There has been a combination of research studies and producer trials evaluating one specific soil biological fertilizer. We are defining a soil biological fertilizer as a material that promotes biological activity in the soil as a means of increasing the nutrient release throughout the season to the growing plant. The soil biological fertilizer used in this study is derived from a patented process that mechanically conditions and complexes poultry manure to produce a stabilized and uniform material containing nutrients and minerals that promotes and accelerates soil biological activity. Analysis of the AgroBiotic fertilizer (Perfect Blend LLC, Bellevue, WA) studied and used in trials shows the following values: N, 8 percent; P_2O_5, 5 percent; K_2O, 5 percent; Ca, 7 percent; Mg, 0.7 percent; S, 3 percent; B, 0.02 percent; Co, 0.0005 percent; Cu, 0.05 percent; Fe, 0.01 percent; Mn, 0.05 percent; Mo, 0.0005 percent; Na, 0.1 percent; and Zn, 0.05 percent, along with mycorrhizal species of *Glomus intraradices, G. aggregatum*, and *G. mosseae*. Studies have been conducted comparing the soil biological fertilizer (Perfect Blend® AgroBiotic 8-5-5) with a commercial enhanced efficiency fertilizer, SuperU® (46 percent N from urea that has N-(n-butyl)thiophosphoric triamide [NBPT] for urease inhibition and dicyandiamide [DCD] for nitrification inhibition incorporated into the urea during the manufacturing process, so each granule has the two inhibitors mixed throughout the granule [Koch Agronomic Services LLC, Wichita, KS]). The experimental design has been to compare corn growth and yield in three tillage systems (chisel plow, strip till, and no-till), all using an N rate of 168 kg ha^{-1} applied preplant. On separate plots, the AgroBiotic was applied in the fall as a broadcast material, and the SuperU was applied as a broadcast material in the spring prior to planting, following the recommendations on the use of this fertilizer. These experiments were conducted on corn during 2012 and 2013 near Ames, Iowa, on a Clarion soil.

Table 1
Yields in continuous corn study in 2012 and 2013 for tillage and N source comparisons

Tillage	N source	Yield (kg/ha), 2012	Std. deviation yield	Yield (kg/ha), 2013	Std. deviation yield
Chisel	PerfectBlend	11753	2546	10330	2621
Chisel	SuperU	9520	1624	9564	1549
No till	PerfectBlend	10453	2189	8480	1662
No till	SuperU	10813	3882	9364	1825
Strip till	PerfectBlend	11409	1374	9954	2025
Strip till	SuperU	11553	2038	10154	2126

These two years saw a large contrast in weather, with 2012 being a severe drought and 2013 characterized as one of the coldest and wettest spring periods on record, followed by below normal precipitation. During 2012, there was an increase in grain yield with the AgroBiotic fertilizer of 600 kg ha^{-1} across all tillage treatments, with a 1500 kg ha^{-1} increase in the chisel-plow system, which also showed consistently greater leaf chlorophyll content throughout the growing season; however, there were no significant differences in yields and chlorophyll content under the no-till and strip-till systems (Table 1). This same effect was observed during 2013, with the AgroBiotic fertilizer producing a 800 kg ha^{-1} yield increase under the chisel-plow system and no significant yield difference in either the strip-till and no-till systems. These observations demonstrate the positive effect of increasing soil biological activity in tillage systems that typically have limited soil biological activity. The initial observations from these field studies have prompted a number of detailed laboratory studies to address the questions about the mechanisms by which biological nutrients affect soil biological activity and nutrient availability. The results suggest that soil water is a major factor affecting the response because in 2013 the decrease in grain yield may have been caused by the excessive water in the field with ponding over many plots. Other research has indicated that Perfect Blend improves soil structure and reduces compaction, thus allowing more rain to infiltrate and percolate to a given tile line; additionally, because soil biological fertilizer has more of its N in amino acids and proteins, it was shown to be 49 percent less leachable than inorganic N forms (Arise Research 2012, unpublished data).

Observations from field-scale studies in producer fields have shown a 1200 to 2000 kg ha^{-1} corn yield increase with the soil biological fertilizer. The tillage system for these trials has been a chisel-plow system, which makes the yield increase similar to what has been observed in plot-scale studies. The primary question emerging from these observations during 2012 and 2013 focused on our lack of quantitative understanding of the role of biological/biotic soil fertility programs on soil microbiological activity and the resultant effects on soil nutrient cycling. Studies of mineralization of N from biofuel by-products, composts, and animal manures have shown rapid organic N mineralization in AgroBiotic fertilizers when compared to other soil biological fertilizers (Moore et al. 2010). This question is being addressed through detailed laboratory studies on soil cores under controlled environmental conditions and represents one of the fundamental questions to be addressed as part of the process to determine why and how materials like AgroBiotic fertilizer affect soil biological activity and the potential limitations to the response.

Initial observations from a variety of producers would suggest that for a range of crops, from tomatoes (*Solanum lycopersicum*) and leafy produce to wheat, corn, tree fruits, and other perennials, that there are benefits to production and to product quality from using AgroBiotic fertilizers. For example, potatoes (*Solanum tuberosum*) grown on several irrigation circles (typically 400 ha per circle) in eastern Washington experienced a 22 percent increase in payables over a 4-year period (Johnson Agriprises 2008–2011, unpublished observations), supporting productivity findings identified by studies in Prosser, Washington, by USDA-ARS (Alva, 2010, unpublished data). In another example on a 400-ha block over 2 years, a large California grower increased average Brix by 3 to 4 points and doubled (grade A) lemon pack-out rate to 53 percent, well above the California Saticoy Lemon Association average of 32 percent (Leavens Ranches 2013, unpublished data). Independently, under the difficult growing conditions during 2013, Renewable Farming LLC test fields in Iowa reported increased yields of up to 25 percent, with 19 percent greater chlorophyll readings, on treated versus untreated corn (Renewable Farming LLC 2013, unpublished data).

There are other commercial grower observations across different climactic conditions and soil types producing results consistent with these preliminary research and producer trials. These observations produce a series of observations that lead to questions about the value of increasing our understanding of soil biological fertility and for increasing the value of manure as a nutrient source through processing.

There are many unknowns in this material that are being addressed: What is the effect on the soil biological system and N mineralization rate? What is the need for continued applications of rates based on nutrient requirements once the soil biological system becomes more functional and active? What is the effect on changing soil properties (e.g., infiltration, SOM) on aggregate stability over time when this material is used? AgroBiotic fertilizers could provide a potential solution because it is an organic source that stimulates and maintains biological activity in cropping systems with reduced tillage while still producing significantly high yields (Hatfield 2013, unpublished data). However, the variation of response in the Midwest across tillage systems confounds the application of a simple recommendation for a management practice and demonstrates the need to quantify the role of soil water and precipitation patterns on the observed response. The linkage between soil water and soil microbial activity will serve as the cornerstone in the development of practical applications of soil biological fertility to achieve desired results.

Conclusions

Feeding the growing world population under conditions of changing climate demands new and innovative solutions to complex problems of soil degradation, to enhance and maintain soil biological systems, and to recycle nutrients contained in manure sources around the world (Walthall et al. 2012). These solutions require us, the agricultural community, to begin to address agricultural systems from a perspective of facilitating soil biological diversity to form the foundation for twenty-first-century soil management decisions and move away from singular approaches in which we examine only the main effects (e.g., nutrient rate or form, tillage, or residue management) and begin to consider the integrated effects of tillage; organic-matter sources; soil physical, chemical, and biological responses; and cropping systems. As the science of soil biology advances, insights about the role of soil biology on soil and plant health—including nutrient status—and ways to manipulate soil biology for better yields, environmental quality, and producer economic viability appear possible.

Although,Abbott and Murphy (2007) provide an overview of the concept of soil biological fertility, the current state of science does not allow evaluation of management practices to achieve this goal. The current state of science reveals that promotion of soil biological activity underpinning soil biological fertility requires a combination of organic nutrients, a stable soil microclimate, and a healthy biological system. Looking at other sources of nutrients to meet future demand, Kellogg et al. (2000) conducted an analysis of nutrients available from production animal manure and concluded that only a few locations had excess manure to meet the nutrient demands required by crops, in spite of the large animal numbers across the United States. This problem will persist unless manures can be converted into more stable, storable, and efficiently transported pathogen-free products, such as what is increasingly occurring with poultry litter converted to AgroBiotic fertilizers. Capturing the value of manure into a soil biological fertilizer will benefit the livestock industry because of the ability to move manure larger distances from the livestock production facilities and increase the ability to increase the nutrient release and availability in the soil for different crops.

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