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The role of plant pathology in understanding soil health and its application to production agriculture

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Abstract. Over the last 10 years, considerable progress has been made in defining and assessing soil health and soil quality. However, problems still exist in the interpretation of soil quality indicators due to the complexity and interrelatedness of soil processes. Additionally, the crop production system selected by growers affects the potential for the adoption of practices promoting soil health. Factors influencing the selection of the crop production system include the marketing strategy adopted by the grower, the commodity value, the cultural practices and inputs used to grow the crop (e.g. fertilisers, pesticides, etc.). To date, growers have had little time to consider the impact of soil health on crop production. Plant pathology, however, and related disciplines have made major contributions to the understanding of soil health, particularly in the area of the identification and verification of disease-suppressive soils and the agents responsible for this suppression. The linkage of plant health to the functional diversity of biological communities in the soil has been far more elusive, but is rapidly becoming more important as consumers and markets push for environmental sustainability. To further progress our understanding of soil health and facilitate its application to production agriculture, plant pathologists should identify and focus on crop production systems that are amenable to showing a return on investment in soil health.

Introduction

Soil health has become an issue of great interest as producers, consumers, regulators and policy makers struggle with the concept of a modern agriculture in which natural resources are conserved, biological diversity is encouraged, pesticide use is reduced, yields are optimised and the financial security of farmers is assured. While the topic of soil health is not new, its relevance to production agriculture was de-emphasised in the generation following World War II as high input, chemically based production systems were designed with the single goal of achieving profits through maximising yields. In the past decade, several unrelated developments have re-ignited the burgeoning interest in soil health. Consumer demand for organic foods has increased dramatically. For example, in the United States, retail sales of organically produced goods have grown by 20% per year reaching US$7 billion in 2000, while in the United Kingdom sales have grown by 40 % per year reaching US$750 million in 1999 (Offner 2000).

Meanwhile, conventional farmers can no longer be assured that chemically based programs for soil disinfestation will be available in the future. Once popular soil fumigants such as ethylene dibromide (EDB) and 1,2-dibromochloropropane (DBCP) have been banned in many countries and methyl bromide, the most widely used fumigant in agriculture, has been identified as a major stratospheric ozone-depleting compound. As a consequence, a global phase-out of its production and sale of methyl bromide is underway (United Nations Environment Programme 1992).

Pest resistance to many popular chemicals continues to increase and disrupt conventional crop protection programs. For example, since 1960, over 200 instances of herbicide resistance in weeds have been reported (Heap 2000) and this number is expected to rise. Finally, rapid increases in population growth have led to conflicts between urban and agricultural interests over water and land use. Subsequent environmental issues have led to dramatic increases in regulations imposed on agriculture by national, regional and local municipalities as they try to institute 'best management programs' for many crop production systems.

For soil health to become a principal component of future agricultural production systems, it is incumbent upon all interests to develop a mutual understanding of the concept of soil health and how it should be measured and sustained. As well, the economic constraints confronting farmers choosing to follow the principles of good soil health management need to be determined. Plant pathology and related disciplines

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Table 1. Parameters used as indicators of either soil health or quality

Indicator	Measurement units
Biological indicators	
Enzyme activity (dehydrogenase, urease, etc.)	mg enzyme kg^{-1} soil h^{-1}
Microbial biomass	μg g^{-1} soil
Population density (genus or functional group)	cfu g^{-1} soil, ppg
Community structure	diversity indices
Plant health	root colonisation, disease incidence
Chemical indicators	
Soil pH	1–12
Organic C, N and C/N ratio	mg kg^{-1} soil
Cation-exhange-capacity	meq $100g^{-1}$ soil
Base saturation (K, Mg, Ca, H, Na)	percent
Extractable minerals (NH_4, NO_3, P, K, etc)	mg kg^{-1} soil
Electrical conductivity	μSiemens
Physical indicators	
Texture	% sand, silt, clay
Bulk density	g cm^{-3}
Porosity	percent
Water infiltration	mL h^{-1}
Rooting depth	cm
Aggregate stability	percent

have contributed much to the body of knowledge pertaining to the biological components of soil health. The objective of this paper is to continue that trend by further identifying the role of plant pathology in understanding soil health and its application to production agriculture.

Defining soil health and soil quality

Many definitions for soil health have been proposed in the previous decade. Most have been used interchangeably with definitions of soil quality, in part because they share many of the same attributes. *Soil quality* can be defined as a set of intrinsic physical, chemical and biological properties that together determine the capacity of a soil to sustain biological productivity, to maintain or enhance environmental quality and to promote plant and animal health (Allen *et al.* 1995; Doran and Parkin 1994; Larson and Pierce 1994; National Research Council 1993). *Soil health* has been defined as the soil's fitness to support crop growth without becoming degraded or otherwise harming the environment (Acton and Gregorich 1995). A more detailed definition is the continued capacity of soil to function as a vital living system within ecosystem and land-use boundaries, to sustain biological productivity, to promote the quality of air and water environments, and to maintain plant, animal and human health (Doran and Safley 1997).

Definitions for soil quality and soil health are similar in that they both recognise that soils have multiple functions extending far beyond maximising yield. Use of the term *soil quality* is preferred by scientists because it infers quantifiable properties or attributes that can be used to assess the capacity of a soil to function and indicates a link between soil properties and function (Romig *et al.* 1995).

On the other hand, soil health implies that soils are a living system (Doran and Safley 1997). Surveys have noted that farmers tend to favor the term *soil health* due to its direct value judgments (healthy vs. unhealthy) (Romig *et al.* 1995). In this paper, *soil health* is used to refer to the condition or state of the soil and *soil quality* to the properties affecting the capacity of a soil to function. It should be noted that as the concepts of soil quality and soil health continue to evolve, the knowledge of soil's many functions increases, and the demands of society change, new definitions will be needed.

Assessing soil health and soil quality

In the mid 1990s, several comprehensive texts defining and evaluating methods to assess the quality and health of soil were published (Doran and Safley 1997). Sets of biological, chemical and physical criteria were proposed for use as indicators of soil health and soil quality (Doran and Parkin 1996; Doran and Safley 1997; Larson and Pierce, 1994). A summary of those sets is presented in Table 1. Additionally, a system was developed to permit farmer-based assessments of soil quality (Romig *et al.* 1996). Use of these indicators as direct measurements of soil health or soil quality is difficult due to the complexity and interrelatedness of soil processes. For example, assessment of soil structure

Table 2. Constraints hindering the implementation of practices promoting soil health in production agriculture

Constraint	Comments
Nature of crop production system	Inherent constraints of some systems are detrimental to practices promoting soil health
Return on investments	Development of healthy soils can take years, no guarantee of success
Measurement of soil health	Biological indicators difficult and expensive to measure
Interpretation of results	Complexity of soil processes limits direct interpretation by producers
Relationship to ecosystem function	Can not predict the expected health and environmental benefits
Impact of disturbance events	Disturbance events are inevitable. What is the potential resilience or resistance of soils?

is done by determining particle size distribution and aggregate stability. These physical indicators of soil quality directly impact on microbial processes in the soil that depend on aeration and have been proposed as a means for estimating the soil's ability to support microbial populations. Conversely, some soil-inhabiting bacteria directly impact on soil structure by promoting the flocculation of soil particles. Determination of which process is responsible for the other is left up to the parties collecting the data.

Another factor complicating the use of indicators for soil health assessment is that soils provide a function for mankind in at least three broad areas: environmental quality, biological diversity and plant health. Although the absolute value of indicators may differ, the same indicators can be used to measure each function. For example, carbon/nitrogen (C/N) ratios greater than 20 are desirable for environmental quality as they indicate immobilisation of inorganic N in soils, thus slowing down the leaching of nitrates into groundwater and local watersheds. For plant health, C/N ratios around 15 are desirable and growth of many crop plants is significantly impaired when C/N ratios are greater than 20, owing to reduced N uptake (Hue and Sobieszczyk 1999). Interpretation of indicators is also complicated by human activities such as tillage or crop selection practices since they can impact on the movement of chemicals into groundwater or watersheds. Therefore, a systems approach to the interpretation of soil health indicators is warranted, although this is often impractical or unobtainable by farmers due to the sheer quantity of information to be managed at the agroecosystems level.

Relevance of soil health to production agriculture

Despite progress in defining the benefits of soil health and identifying indicators used to measure it, the concept of soil health and its implementation has not been widely embraced by the agricultural production industry. Limitations to its adoption by mainstream agriculture have been discussed (Herrick 2000; Jaenicke 1998; Karlen *et al.* 1997) and are summarised in Table 2. A major constraint to the adoption of practices promoting soil health that has not received adequate attention is consideration of the crop production system itself.

Crop production systems can be classified in several different ways – by the marketing strategy, the commodity value, the cultural practices or by reference to the selection of inputs (pesticides, fertilisers, etc.) (Table 3). The marketing strategy has a strong influence on the nature of the crop production system. In bulk production systems, crops are grown on a large scale and marketed by either commodity traders (brokers), contracts with processors, or through the internal mechanisms of large corporations

Table 3. Relationship of crop production factors to likely adoption of soil health

Marketing strategy		
Bulk productions systems	*Direct marketing systems*	
Require large capital investment, designed to operate under economies of scale	Small scale, highly decentralised	
Decisions made at the corporate level	Farmer control over production	
Commodity value		
High cash value systems	*Low cash value systems*	
Require large capital investment	Narrow profit margin, seek to minimise inputs	
Demand a high quality product	Opportunity for long-term decisions	
Cultural practices and selection of inputs		
Conventional	*Organic*	*Conservation tillage*
Can use all available options	Must use approved biologically based inputs and cultural practices	Minimise tillage, but rely on herbicides
Good soil health more difficult and less likely to be achieved	Based on concepts promoting soil health	

(vertical integration). In contrast, direct marketing systems are generally small-scale businesses where crops are marketed by direct transactions with the retailer or consumer. The two systems are separated by their economies of scale and the amount of control growers have on the operations in the field.

Due to their size and the capital needed, bulk producers relying on commodity traders to sell their crops must obtain extended lines of credit to finance the next year's crop. Thus, they are less inclined to make decisions that offset immediate profits for tangible gains in the distant future, including those that invest in soil health. In bulk production systems where crops are grown under contract or directly by large corporations, decisions regarding crop production practices are often made at the corporate level with little input from the grower on the farm. Under this scenario, it is highly unlikely that the health of the soil on individual farms and the extended environmental and social benefits it may have on surrounding communities will be given the same weight in the decision making process as short-term profitability.

By contrast, in direct marketing operations, farmers exercise substantial control over their products from cultivation to final sale and are more likely to make decisions favourably impacting on the long-term health of their soils. Because direct marketing operations are generally small-scale businesses and highly decentralised, they are more likely to risk short-term profits for the potential gains associated with soil health.

The commodity value of the crop also dictates the nature of the crop production system. High value crops include vegetables such as tomato, strawberry and pepper, and ornamentals such as cut flowers, bulbs and foliage plants. While the harvested crops generate high returns, they must also be of high quality and meet stringent market windows. These demands require extensive inputs for crop growth and pest and disease control resulting in production costs exceeding US$28 500 per ha (Smith and Taylor 2000). To protect their investment and minimise the risk of crop failure, growers rely on soil fumigation to control soilborne pests. In some instances, lending institutions even require growers to fumigate soil with methyl bromide as an insurance against crop failure due to soilborne pests. Under this scenario, implementation of practices promoting soil health will be difficult.

The problem is further exacerbated because many of these high value commodities are produced in regions where arable land is limited and must be rented. The combination of high rents and the prospect of moving off the land in the near future are not conducive to implementing a long-term approach to promote soil health. On the other-hand, low cash-value crops such as small grains, forage and other agronomic crops are grown in situations where the profit margin is narrow and the additional use of inputs does not result in increased returns. Since growers must often seek creative ways to manage their systems without the use of additional chemical inputs, the potential for implementation of practices promoting soil health is greater under this scenario.

Crop production systems may also be divided along the selection of inputs and cultural practices. Conventional farmers may choose from a wide selection of materials and practices for the cultivation of their crops. Chemical inputs such as pesticides and mineral fertilisers can be used alongside biologically based inputs such as composts, cover crops and biocontrol organisms. Implementation of procedures to promote soil health is left up to the individual grower. Organic production systems are limited to the use of biologically based inputs and have evolved around the use of practices that promote soil health. Conservation tillage production systems are also based on the concept of soil health and incorporate practices to promote it.

Plant health management versus soil health

In a recent review, Cook (2000) described plant health management as 'the practice of overcoming the succession of biotic and abiotic factors that limit plants from achieving their full genetic potential', including maximising yield and quality. Comparison of cropping systems ranging from broad acre wheat to intensively cultivated horticultural crops reveals a vast difference in the way growers manage plant health in relation to soil health. For many agronomic crops such as wheat, barley and oats, these two factors appear to be directly correlated as an increase in soil health generally improves plant health. The fact that high cost inputs can not be used economically in many agronomic systems forces growers to use less expensive inputs and instead to target improvements in soil health, with subsequent effects on plant health.

For intensively cultivated horticultural crops, soil health and plant health may often be inversely correlated, especially in situations where growers aim to obtain absolute yields (Cook 2000). This is particularly evident in fumigated soils because fumigation destabilises the natural equilibrium; that is, it increases plant health at the expense of soil health. Development of an understanding of why many plants respond favourably to fumigation is assisting in the identification of soil health factors that are most likely to impact on plant growth and disease protection (Porter *et al.* 2000). To this end, a global phase out of methyl bromide will ultimately lead to an increase in knowledge of soil health and will indirectly assist in the development of improved sustainable IPM systems for disease control.

For example, why do yields of many crops increase substantially after soils are fumigated? Reports have shown that yields of wheat, strawberries, flower crops, etc. can be improved by up to 70% in fumigated soils (Cook 2000; Porter *et al.* 2000). These yield responses, often termed the increased growth response (IGR), have not just been attributed to control of major and minor soilborne pests and pathogens, but also to changes in the nutrient and microbial status of the soils (particularly nitrogen) which favours plant health. Results also suggest that increases in availability of NH_4-N and other plant nutrients caused by the reduction in microbial numbers may also contribute to the growth response after fumigation (Porter *et al.* 1999*a*). Soil fumigation consistently increases ammonium-N (NH_4-N) in soil, mainly as a result of death of microorganisms and a decrease in the rate of mineralisation and nitrification (Hansen *et al.* 1990). This NH_4-N is available for plant growth and can be preferentially taken up instead of nitrate by many plants (Huber and Watson 1974). It has also been well established that fumigated soils are rapidly colonised by soil bacteria, particularly gram negative bacteria (Porter *et al.* 1999*a*, *b*), many of which, especially the nitrifiers, take advantage of the high NH_4-N to produce nitrate (NO_3-N). It is likely that this acts in much the same manner as a slow release nitrate fertiliser, supplying nitrate to the roots of plants in increasing amounts until the NH_4-N concentration again reaches an equilibrium similar to that in non-fumigated soils. As ammonium is less soluble than nitrate, fumigation also ensures that nitrogen, as nitrate is not leached from soils. Porter *et al.* (1999*a*) also identified that soil concentrations of many other nutrients, electrical conductivity and pH were all altered in fumigated soils and although these factors obviously had an impact on both plant and soil health, the exact relationship still needs to be determined.

The scenario proposed above is just one reason why some growers of high value horticultural crops have trouble adapting IPM programs that promote soil health. So how do these growers and an environmentally conscious society in the 21st century cope with products, such as fumigants, which have such drastic effects on soil health and biodiversity? One solution may be that in future many more high value horticultural crops will be produced in soilless production systems where soil health is of minor importance, but plant health can be maximised by controlling inputs (fertilisers, water, etc.). Moves in this direction have already occurred for many crops. In the last decade in Europe, a massive expansion has been seen in the area and a number of crops are grown in protected cropping systems using sands or other soilless cultures as growing medium. Is this the future trend for the rest of the world?

Contribution of plant pathology and related disciplines

Major contributions to the understanding of soil health have been made over the years by studies in plant pathology, nematology and microbiology (Cook and Baker 1983; Hornby 1983). A key example is the identification and verification of disease suppressive soils (Hopkins *et al.* 1987; Murakami *et al.* 2000; Westpahl and Becker 2000) and of the agents responsible for their suppression (Larkin *et al.* 1996; Mazzola 1999; Scher and Baker 1980; Westphal and Becker 2001). Other areas of significant contributions include identification of the biological processes responsible for negative effects associated with programs to improve soil health (Cook and Haglund 1991).

The linkage of plant health to the functional diversity of biological communities in the soil is another area in which plant pathology and related disciplines have made great strides. With up to 4000 genetically different kinds of bacteria present in a single soil sample (Torsvik *et al.* 1990), broad estimates of bacterial populations do not provide enough information to assess the health of a soil. Characterisation of microbial diversity must be correlated to key soil functions to further elucidate our understanding of soil health. Standard estimates of population density alone are not sufficient to determine the health status of soils. Studies in plant pathology have shown that the relative abundance of key species or functional groups within specific agroecosystems can be the primary determinants of disease suppression (Mazzola and Gu 2000; Postma *et al.* 2000; Raaiijmakers and Weller 1998).

New techniques have been developed to characterise microbial diversity in soils (Garland and Mills 1991; Ogram 2000; Ranjar, *et al.* 2000; Zak *et al* 1994) and can be used to increase knowledge of disease suppressive soils. One example is the development and use of a rapid polymerase chain reaction-based assay to characterise rhizosphere populations of bacteria producing 2,4-diacetylphloroglucinol (McSpadden Gardener *et al.* 2001). These bacteria are associated with disease suppressive soils and the development of an accurate and efficient method to quantify their abundance will facilitate future studies of their contribution to the suppression of plant diseases.

The direction for future research

To continue the progress in understanding soil health and facilitating its application to production agriculture, plant pathologists must address the constraints outlined in Table 2. As noted earlier, not all crop production systems are amenable to the concepts of soil health (Table 3). Systems with the highest potential for successful application need to be identified and efforts focused on those systems. Studies addressing the long-term biological impacts of crop production systems are needed to provide a comprehensive assessment on the return on investment in soil health. Comparative studies of the biological impacts of cropping systems represent a good starting point. For example, a comparative study of organic and conventional tomato production systems found that incidence and severity of several soilborne diseases were significantly higher in conventional systems and highly correlated with soil nitrate (Workneh *et al.* 1993).

Technology for the measurement of soil health and the interpretation of results remains out of the reach of most commercial growers. But is it necessary for every grower to have access to laboratories performing polymerase-chain-reaction (PCR) technology to ascertain the health status of their soils? For generations, growers and researchers alike have known that key cultural practices such as addition of organic matter and crop rotation have had enormous impacts on soil health and, when used correctly, can produce disease suppressive soils. On the other hand, minimising the risk of crop failure is essential to encourage more growers to adopt practices promoting soil health. Molecular methods such as PCR technology are very powerful tools to determine whether growers have achieved the proper balance of beneficial microbes in soil.

Some major disturbance or stress events such as drought, frost or flood are inevitable. Others such as tillage, fumigation or herbicide application are avoidable. The sustainability of soil health will remain in question until information is available to assist growers in understanding the consequences of their crop production practices. Determination of the stability and resilience of soil to disturbance events will allow growers to identify the impacts of their cultural practices on soil health. Traditional methods consist of correlating a list of indicator variables with the incidence of plant disease or the pattern of disturbance events. One novel method proposed has been to measure the amplitude and frequency of fluctuations in microbial populations along the length of the root system (van Bruggen and Semenov 1999). Another more simplistic approach has been to characterise changes in the communities of root colonising fungi (Chellemi and Mitchell, unpublished data).

Conclusion

A healthy soil offers many benefits to farmers and society, including sustained biological productivity of the land, improved quality of air and water environments, and the maintenance of plant, animal, and human health. Although in the last ten years, considerable progress has been made in defining and measuring the factors contributing to soil health and soil quality, the majority of mainstream agriculture has not embraced the use of crop production systems designed to improve soil health. Plant pathology and related disciplines have contributed greatly in identifying and measuring the biological parameters associated with healthy soils and in understanding the mechanisms by which disease suppressive soils function. However, additional contributions by plant pathology will depend on addressing the constraints that have limited the implementation of practices promoting soil health. Understanding the limitations of the crop production systems used by growers is vital. Additionally, production systems that focus on plant health and yields at the expense of soil health are not amenable to implementing practices promoting soil health and, therefore, the contributions of plant pathology and related disciplines will be minimal. Of the crop production systems that can more easily adopt practices promoting soil health, information defining the impact of disturbance events and the broader effects on ecosystem function will be of great benefit. Ultimately the aim is to develop an understanding of how soil health standing can be manipulated to not only maximise grower profits and crop yields, but also achieve environmental sustainability.

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