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Soil health indicators and Fusarium wilt suppression in organically and conventionally managed greenhouse soils

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ABSTRACT

Soil health has been associated with internal cycling of nutrients, microbial activity and diversity as well as root disease suppression, which are frequently greater in organically than in conventionally managed soils. Resistance and resilience, measured as amplitude and frequency of oscillations in bacterial communities after a disturbance, were suggested as integral indicators of soil health, but until now there is little proof for this hypothesis. In this study, resistance and resilience of microbial communities and 24 soil chemical and biological parameters were analyzed and correlated to suppression of flax wilt (caused by *Fusarium oxysporum* f.sp. *lini*) in three experiments. Soil samples were collected on three different dates from a recently converted organic greenhouse and a similar, neighboring greenhouse under conventional management. The dynamics of copiotrophic and oligotrophic bacteria after a disturbance were monitored, and the resistance and resilience were calculated. The organic soil showed significantly higher water-holding capacity, organic matter content, total C and N contents, C:N ratio of the small particulate organic matter fraction, microbial biomass carbon, oxygen uptake rate, copiotrophic and oligotrophic bacterial communities and suppression of flax wilt incidence. After incorporation of a grass–clover mixture in both soils, the densities of copiotrophic and oligotrophic bacteria oscillated over time. The relative amplitudes of the oscillations (in grass–clover amended over non-amended soil) and the frequencies of the oscillations of both trophic groups were lower for the organic soil, indicating that the resistance and resilience of the microbial community were greater in this soil. These results support the hypothesis that the bacterial response to a disturbance can serve as an integral indicator for soil health, including disease suppressiveness.

1. Introduction

Soil management in organic farming systems differs from that in conventional farming systems by the lack of synthetic pesticides and mineral fertilizers and the greater use of organic inputs such as composts and animal or green manures (Drinkwater et al., 1995). Organic farmers generally use wider crop rotations and less intense soil tillage (Leoni et al., 2014). However, the variation in management practices and soil quality is considerable, for both conventional and organic farming systems (Franz et al., 2008; van Diepeningen et al., 2006). Various comparative studies have been conducted in which soil chemical parameters were determined for conventional and organic or low-input systems. The results of these studies vary considerably. Clark et al. (1998b) reported that the inputs of C, P, K, Ca, and Mg to soil were higher in organic and low-input systems than in the two conventional systems as a result of manure applications and cover crop incorporations in the former systems. However, Mäder et al. (2002) reported lower inputs of N, P and K in their organic than in the conventional systems. Soil nutrient levels varied accordingly. Higher levels of total and organic C, total N, and soluble P were reported for organic soils (Clark et al., 1998b), whereas Mäder et al. (2002) reported small differences for soil chemical parameters like organic C and P. Soil mineral N levels during the cropping season varied by crop, farming system and the amount and source of N fertilization (Poudel et al., 2001). Nevertheless, N availability was most important in limiting yields in the organic system (Clark et al.,

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1999). Soil pH was slightly higher in the organically managed than in the conventionally managed soils (Clark et al., 1998b; Mäder et al., 2002).

More consistent differences have been found for biological soil parameters. A higher microbial activity (Mäder et al., 2002; Workneh and van Bruggen, 1994b) and biomass (Fliessbach et al., 2007; Mäder et al., 2002) have commonly been found in organically than in conventionally managed soils. Most organically managed soils have also a higher diversity of bacteria (Mäder et al., 2002; van Diepeningen et al., 2006; Workneh and van Bruggen, 1994a), fungi (Swer et al., 2011), nematodes (van Diepeningen et al., 2006), earthworms (Mäder et al., 2002), and arthropods (Drinkwater et al., 1995; Mäder et al., 2002) than conventionally managed soils.

Highly diverse ecosystems with numerous taxa that form a complex food web with many trophic levels are generally considered to be healthy, thriving ecosystems (Duffy et al., 2005). Therefore, taxonomic and functional diversity indices are often used as indicators for the health status of soils (van Bruggen and Semenov, 1999; van Diepeningen et al., 2006). Cultivated soils often have lower microbial diversities than they had as a natural habitat (e.g., Buckley and Schmidt, 2001), and in this respect, agricultural soils managed organically look more like natural soils.

A healthy soil is further also defined as a stable system with resistance and resilience to stress or a disturbance (van Bruggen and Semenov, 1999). van Bruggen and others described earlier that soil microbial densities fluctuate, and start to oscillate regularly in response to a disturbance, such as addition of organic material to soil (He et al., 2010, 2012; van Bruggen et al., 2006; Zelenev et al., 2000, 2005a, 2006). They suggested that the amplitude of the waves in microbial densities, their frequency, and the time needed to return to initial conditions before organic amendment may be used as indicators for soil health (van Bruggen and Semenov, 1999). This means that resistance and resilience of microbial communities to a disturbance could be related to disease suppression (van Bruggen and Semenov, 1999; van Bruggen et al., 2006). Indeed, soils with a higher biological diversity and activity, such as natural or organically managed agricultural soils are frequently more suppressive to root-infecting fungi or bacteria than conventionally managed agricultural soils (Grünwald et al., 2000; Hiddink et al., 2005; Messiha et al., 2009; van Bruggen et al., 2014; Workneh and van Bruggen, 1994a,b). Even human enteric pathogens tend to be suppressed more in organically than in conventionally managed soils and inside tomato plants grown in organically managed soils (Franz et al., 2008; Semenov et al., 2008). However, the relationship between resistance and resilience of soil microbial communities after a disturbance and root disease suppression has not been demonstrated until now. Thus, although microbial resistance and resilience were suggested as integral indicators of soil health (van Bruggen and Semenov, 1999; van Bruggen et al., 2006), there is little proof for this hypothesis at the present time.

Soil suppressivenes to Fusarium wilt caused by various forma speciales of *Fusarium oxysporum* is well known (Amir and Alabouvette, 1993). Suppression of *F. oxysporum* is often enhanced after amendment of soils with organic materials (Bonanomi et al., 2007). Application of compost or a mixture of compost and manure are generally more effective than crop residues (Bonanomi et al., 2007; Senechkin et al., 2014; Serra-Wittling et al., 1996). However, the effect of plant residues on populations of *F. oxysporum* depends very much on the particular crop providing the residues (Leoni et al., 2013). Moreover, the effects of amendments such as composts are not always the same for different plant pathosystems (Bonanomi et al., 2010; Termorshuizen et al., 2006). Nevertheless, repeated applications of organic materials, in particular of compost, as done in organic farms, has led to suppression of Fusarium wilt of melons (Yogev et al., 2011) and other vegetable crops (Yogev et al., 2006). Suppression of Fusarium wilt is usually more related to microbial characteristics and enzymatic activities than to any of the chemical soil parameters tested (Bonanomi et al., 2010; Borrero et al., 2004; Yogev et al., 2011). Certain microbial groups such as oligotrophic bacteria and actinomycetes or non-pathogenic *Fusarium* species seem to be more associated with disease suppression than other groups (Borrero et al., 2004; Wei et al., 2012; Workneh and van Bruggen, 1994a). We hypothesize that a large microbial diversity, with a relatively high proportion of oligotrophs, dampens the oscillations in microbial communities and in easily available carbon sources after a disturbance, thereby reducing the ability of soilborne pathogens to infect roots (van Bruggen et al., 2006; Zelenev et al., 2006). However, again, resistance and resilience of microbial communities after a disturbance were not included as a soil health parameter in the disease suppression studies cited above.

The main aim of this study was to investigate if the resistance and resilience of the microbial community, as measured by the amplitude and frequency of bacterial oscillations after amendment of soil with grass–clover residues, was related to suppression of *F. oxysporum* f.sp. *lini* on flax. An additional aim was to relate disease suppression to 24 soil physical, chemical and biological parameters that are commonly used as other potential indicators of soil health. To address these aims, three independent samples from an organically and a conventionally managed greenhouse were used to measure all soil parameters, Fusarium wilt suppression and the daily dynamics of copiotrophic and oligotrophic bacteria in soil with and without disturbance, viz., amendment with grass–clover residues. The effect of these residues on Fusarium wilt was also determined.

2. Materials and methods

2.1. Greenhouse experiment

In autumn 2003, an experiment was set up in two identical greenhouse compartments (150 m^2 each) with a similar history of conventional production to compare various systems of greenhouse tomato production, including an organic soil-bound system and a conventional soil-bound system (Gravel et al., 2010). The soil was a sandy soil with the following characteristics at the beginning of the experiment: pH_{KCl} 5.7; organic matter content 9.3%; clay content (particles $< 2\ \mu m$) 8%; $CaCO_3$ 0.2%. In both greenhouse compartments, the soil was rototilled to a depth of 25 cm (Fig. S1A and B). Tomato production in the greenhouse generally results in very high yields (300–500 mT/ha over a period of 9 months), and thus requires large inputs, particularly of nitrogen. The organic compartment received 153 tons ha^{-1} of composted green waste and 109 tons ha^{-1} of partially decomposed cow manure, which was incorporated with a rototiller to a depth of 15 cm. Subsequently a mixture of common vetch (*Vicia sativa*) and rye (*Secale cereale*) was sown. In the winter of 2004/2005, composted green waste (157 tons ha^{-1}) and cow manure (27.3 tons ha^{-1}) were again applied in the organic compartment. The conventional greenhouse did not receive any inputs until the start of the tomato growing seasons in 2004 and 2005. The nutrient inputs during the tomato growing seasons were based on the advice of a commercial soil analysis laboratory to which soil samples were sent every 3–4 weeks. The advisories were specific for each production system and similar to commercial conventional and organic tomato production systems. In the conventional compartment only mineral fertilizers (N–P–K = 12–10–18) were applied; in the organic compartment only fertilizers that are allowed in certified organic production, namely organic manure pellets (Culterra 10-4-6, Culterra, Workum, the Netherlands) and Epsom salt (containing 16% MgO). The total amounts of N, P and K applied in 2005 were