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Earthworms and nitrogen applications to improve soil health in an intensively cultivated kiwifruit orchard

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ABSTRACT

Integrated approaches which simultaneously consider how intensification affects soil biota and the processes they regulate assist in developing sustainable management practices. Therefore, in this study, we investigated the effect of introducing an anecic earthworm (*Lumbricus friendi*), in combination with two nitrogen applications either via biological fixation (clover, +EC) or cattle manure (+EM) on the chemical properties of an horticultural soil (C release, N mineralisation, soil pH, cations and P availability) collected from a kiwifruit orchard where the fruit is intensively produced using conventional agriculture practices. The laboratory incubation study also included two controls with and without earthworms (+E and −E, respectively) replicated 15 times. Results from destructive sampling across 5 sampling occasions showed that the addition of an organic fertiliser had a positive effect on the earthworm biomass, C and N mineralisation, and nutrient availability (namely Mg, K and assimilable P), suggesting that the organic matter provided was very accessible to microorganisms and earthworms. In contrast, the inclusion of a N-fixing legume did not have similar positive effects on the health of these agricultural soils, which could be a reflection of an unsuccessful nodulation and P limitation. Importantly, up to 85% of the total amount of nitrogen leached from these treatments consisted of dissolved organic nitrogen, which represents a significant N pool and could have economic and environmental implications, but could be controlled by synchronising application rates with crop demands. These results suggest that the combined effects of earthworms and animal manures supply the soil with a good source of both nutrients and microbial populations and provide a more sustainable management of these agro-ecosystems than conventional agriculture.

1. Introduction

Kiwifruit (*Actinidia deliciosa* (A. Chev) CV Liang & A.R. Ferguson) is a perennial vine which is cultivated in several European countries, with Spain occupying the 11th position (FAOSTAT, 2008). In particular, the Galician region (NW Spain) yields up to 64% of the gross national production (MAPA, 2007) and therefore, it is intensively cultivated in this area to satisfy the commercial demand. Due to continuous technological advances, intensive agricultural practices, including the use of heavy machinery and applications of herbicides, phytosanitary measurements and/or inorganic fertilisers, have successfully improved fruit yield, at least in the short-term. However, the long term performance of these horticultural systems is seriously compromised by the severe detrimental effects that such practices have on soil fertility and soil organisms (Susilo et al., 2004; Hole et al., 2005; Postma-Blaauw et al., 2010). Because soil biota are key players in providing nutrients (e.g. through soil organic matter decomposition and nutrient cycling) and promoting soil structure and maintenance (e.g. through burrowing and aggregate formation), they also have an essential role in promoting plant growth (Laakso and Setälä, 1999; Wardle et al., 2001).

Consequently, the current trend in agriculture is to seek ‘sustainable’ practices which provide farm profitability by counteracting some of the critical limiting factors of crops’ productivity, namely water availability and removal of nutrients (Crew and Peoples, 2004). Traditionally, soil organic matter (SOM) quality has been evaluated in terms of C/N ratios; however, the amount and availability of essential biological nutrients, including nitrogen (N) (e.g. Berry et al., 2002), phosphorus (P) (e.g. Sirkar et al., 2000) and water soluble SOM (e.g. Haynes, 2000) are key regulators of carbon processes and could limit crop productivity. Consequently, sustainability implies being self-sufficient in providing all these nutrients through, for example, the fixation of N_2 by legumes (Berry et al., 2002), recycling the crop residues (Elfstrand et al., 2007) and applying natural resources such as farmyard manures,

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composts, vermicomposts and biofertilisers (Ravindra et al., 2007). However, organically produced crop residues and manures tend to have low N contents and slow mineralisation rates (Berry et al., 2002) and on the other hand, phosphorus is not a renewable natural resource and hence, it has to be added in organic or mineral forms or by treating the seeds with phosphate solubilising bacteria (Mohammadi et al., 2009).

In addition to this, soil pH could also be a limiting factor for agricultural production as a result of toxic levels of aluminium and manganese and suboptimal levels of phosphorus (Kochian et al., 2004). In particular, Galician soils are characterised by low pHs due to parent material being of granitic nature and molar concentrations of aluminium extracted with pyrophosphate usually range between 2 and 29 $g\,kg^{-1}$ in the mineral horizons (Pontevedra-Pombal, 2002), which could represent important limitations for kiwifruit growth (Otero et al., 2007).

Compared with these chemical parameters, soil biological properties have seldom played a role in agricultural assessment (Van Eekeren et al., 2010). However, soil biodiversity contributes greatly to the efficiency of the resource use, confers disease suppressiveness and provides resistance against disturbance and stress (Brussaard et al., 2007). Among the soil macrofauna, earthworms are considered to be 'biological indicators' of the welfare of the agroecosystem since they rapidly respond to management changes (Perés et al., 2008; Van Eekeren et al., 2008; Postma-Blaauw et al., 2010). They have an important role in soil fertility by improving soil structure and drainage and transforming SOM into rich humus (e.g. Bossuyt et al., 2004, 2006; Srinithi and Brian, 2010). Furthermore, they also increase the densities of microorganisms (up to 5 times greater than control soils; Atlavinyté and Luganskas, 1971), facilitate the dispersal of fungal spores and mycorrhizae and, as a result of these interactions, they can increase the levels of plant growth regulators, enzymes and other chemical stimulators (Krishnamoorthy and Vajranabhaiah, 1986; Noguera et al., 2010). There is also evidence that bacterial gums aggregate mineral particles in the earthworm gut (Swaby, 1950). In addition, the cast material shows greater stability (Bottinelli et al., 2010), higher pH and moisture and is richer in C, N, Ca^{2+}, Mg^{2+} and K^{+} and polysaccharides (Jouquet et al., 2008) than the surrounding soil and hence, it is a hotspot for microbial activity (e.g. Kladivko, 2001). Positive correlations between aggregate stability and soil microbial processes have led to the conclusion that plant roots and heterotrophic organisms are important in maintaining soil structure (Kandeler and Murer, 1993) and consequently, most productive soils, which are desirable for agriculture, have a crumb or granular structure (Jacks, 1963).

The ecological role that earthworms play in soil processes is conditioned by the different burrowing capabilities and feeding habits exhibited by the different species which have resulted in them being classified into different ecological categories (Bouché, 1971, 1977). In contrast to natural ecosystems, in intensively cultivated lands earthworm populations are generally less abundant due to the detrimental effects of agricultural practices on their survival (e.g. mechanically induced disturbance, decrease in the amount of organic matter available as a food source, removal of the protecting litter layer and increase of predation by birds as a result of earthworms brought back to the surface). Consequently, higher mortality rates of predominantly epigeic and anecic earthworms have often been recorded, ranging from 25% in several crops of Switzerland (Cuendet, 1983), 50% in potato crops of Australia (Buckerfield and Wiseman, 1997), 60–70% in Swedish grasslands (Boström, 1988) to earthworms being almost totally absent from intensive potato plantations in Ireland and from arable crops in The Netherlands (Curry et al., 2002; Van Eekeren et al., 2008). Anecic earthworms build vertical burrows usually reaching between 1 and 2 m depth and move up and down to feed (preferentially at night) on fresh organic inputs on the soil surface (Edwards and Bohlen, 1996). In the lining of their burrows organic C sequestration has been shown to be enhanced by 270–310 $g\,m^{-2}$ (rate 22 $g\,C\,m^{-2}\,yr^{-1}$; Don et al., 2008) and it is also enriched in N transforming bacteria (Parkin and Berry, 1999). Furthermore, as a result of these tunnelling activities, some anecic species can also form middens (small mounds of worm casts and residues at the opening of the burrow; Kladivko, 1993), which are also localised spots for increased microbial activities and nutrient cycling (Schrader and Seibel, 2001; Bohlen et al., 2002). Therefore, the absence of their burrowing activities in arable soils has important implications for crop performance as a result of impoverished water infiltration and root growth (Bouché and Al-Addan, 1997) as well as less incorporation of SOM and crop residues (Svendsen and Baker, 2002; Amador et al., 2003; Giannopoulos et al., 2010).

In view of all this, more recently 'soil health' and the closely related concept of 'soil quality' have been coined to better describe the general condition of the soil resources and their capacity to respond to human intervention (Kibblewhite et al., 2008) instead of 'soil fertility' which has usually been associated with crop yield (Siegrist et al., 1998), Therefore, in this study, we evaluated the combined effect of introducing an anecic earthworm species (*Lumbricus friendi* Cognetti, 1904) with either planting a nitrogen fixing legume or adding cattle manure on several chemical properties of an intensively cultivated horticultural soil under laboratory conditions to provide a more sustainable management of these agroecosystems. We hypothesised that due to its high C:N ratio, manure application will supply carbon to microorganisms and earthworms but will release N at much slower rate than leguminous crop (Berry et al., 2002). Our main aim was to investigate whether biotic influences through their direct (e.g. burrows which increase water infiltration and organic matter incorporation) and indirect activities (interactions with microorganisms) would extend the potential benefits of these two common management practices and thereby increase the soil quality of these intensive managed systems.

2. Materials and methods

2.1. Study site

The experimental plot belonging to the company Kiwi España S.A. is located in Tomiño, Pontevedra (NW Spain; 42°00′34″N, 8°43′3″W, 80 m a.s.l.). The kiwifruit orchard (*A. deliciosa* [Chev.] C.F. Liang & A.R. Ferguson var. *deliciosa)* covers approximately 1 ha and is planted with kiwifruit vines in rows 4 m apart with adjacent vines within each row being 4 m apart. Vines were trained to grow onto T-bar trellises with alternation of female and male plant rows in the proportion of 4:1 (f/m). The fruit is intensively produced under the typical conventional treatment in the area, which involves addition of inorganic fertilisers by ferti-irrigation during the vegetative growth (April–November, total annual nutrient input of 150 $kg\,N\,ha^{-1}$, 25 $kg\,P\,ha^{-1}$, 200 $kg\,K\,ha^{-1}$, and 45 $kg\,Mg\,ha^{-1}$). The soil is classified as Dystric or Gleyic cambisol (FAO, 1998) with relatively low pH ($pH_{H_2O} = 4.8 - 5.8$), relatively rich in organic matter (7% C) and low to moderate nutrient (assimilable P, K, Mg and Ca) levels (Merino et al., 2006).

The area is under an oceanic influence with a moist temperate climate characterised by an annual average temperature of 14.1 °C and precipitation of 1388 mm for the period 2001–2008 (data from the closest meteorological weather station located at As Eiras-O Rosal (41°56′N, 8°47′W, 60 m a.sl); Meteogalicia, Xunta de Galicia; www.meteogalicia.es).

2.2. Sampling and experimental set-up

In December 2005, 60 intact soil cores (11 cm diameter × 16 cm deep) with their associated vegetation were collected from the