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Increase in soil nematode abundance due to fertilization was consistent across moisture regimes in a paddy rice–upland wheat system

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ABSTRACT

Nematodes exert top-down control on the microbially-mediated processes of decomposition and nutrient cycling due to their position in the soil food web. Fertilization of agricultural soils can increase substrates for nematode populations, but whether the nematode community response to fertilization is consistent under anaerobic and aerobic soil conditions is not known. Our study investigated how soil nematode abundance and community structure responded to fertilization of a double-cropping system with paddy rice, representing anaerobic soil conditions due to flooding, followed an upland wheat phase that was rainfed and predominantly aerobic. We examined nematode communities twice a year from 2011 to 2013 at the ripening stage of rice (October) or wheat (June). Five fertilizer treatments were compared, including control (CK), chemical fertilizer (CF), compound pig manure-chemical fertilizer (MCF), straw plus chemical fertilizer (SCF) and pig manure plus straw plus chemical fertilizer (MSCF). Total nematode abundance increased by fertilization consistently in the rice and wheat cropping phases, and straw addition (i.e. SCF and MSCF) showed higher increment than manure addition (i.e. MCF) and CF treatments. However, dominant nematode genera respond to fertilization differently, depending on the crop phase. This is because dominant genera in the anaerobic soils of the rice phase were the plant-feeding nematode *Hirschmanniella* and algae-feeding nematode *Rhabdolaimus*, whereas dominant genera in the aerobic soils of the wheat phase were the fungal-feeding nematode *Filenchus* and bacterial-feeding nematodes *Cephalobus*, *Eucephalobus* and *Acrobeloides*. The manure addition (i.e. MCF) significantly raised *Hirschmanniella* abundance (by 133–616%) but sharply reduced the *Rhabdolaimus* population by 115–774% in the rice phase. In addition, straw addition (i.e. SCF and MSCF) increased *Filenchus* numbers (18–118%) but decreased the *Acrobeloides* population (49–145%) in the wheat phase. Since the MCF, SCF and MSCF fertilizers supply organic substrates for microbes and nutrients for plants, both of which are consumed by nematodes, this implies that food resources are the key determinant of total nematode abundance, the population size of all trophic levels. Our findings show that the nematode community structure is distinctive for each crop grown under a particular soil moisture regime, and that food resources derived from fertilizer inputs act as a bottom-up modulator of nematode population size in paddy rice–upland wheat systems.

1. Introduction

Occupying a central position in the soil food web, nematodes are considered an integrative bioindicator of soil ecological functions [1,2]. Nematodes modulate nutrient cycling and energy flow through the soil food web by feeding on plants and microbes, and are in turn consumed by predators from higher trophic groups (e.g. arthropods and earthworms). They respond positively when food resources are in greater supply, and larger population sizes are expected when nematode growth and reproduction are not limited by soil environmental conditions or biotic factors.

Agricultural soils possess ample food resources for nematodes,

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which may be enhanced by adding fertilizer. Organic fertilizers (e.g. animal manures, crop residuals, green manure and composts) not only supply nutrients for crop production and soil fertility improvement, but they also promote soil biodiversity [3,4]. However, the response of nematode trophic groups to organic fertilizers tends to be controlled by the quality of the organic material [5]. Swine manure addition significantly increased the plant-feeding nematodes compared to the control or crop residue amendment, whereas crop residue greatly raised the abundance of fungal-feeding nematodes [6]. Nematode populations are 30–120% larger when manure is applied because of the greater supply of organic matter for microbial growth than with chemical fertilizer [6–8]. Still, chemical fertilizers may promote total nematode abundance by 15–90% relative to control plots that receive no fertilizer, probably due to the beneficial effect of fertilizer on crop growth, leading to more rhizodeposits or residues that serve as substrates for microorganisms and nematodes [8]. Organic fertilizers are often combined with chemical fertilizers to enhance crop yield and improve soil quality [9], and this combination was found to significantly increase the abundance of soil microbes and nematodes that feed on microbes [6,7,10].

Fertilizers are necessary for profitable crop production, particularly in regions where two crops are grown per year on the same field. An example of this double-cropping system is an annual summer rice–winter wheat rotation, the dominant farming system on 60% of the paddy fields in southeast China [11]. During the year, the soil moisture regime shifts from anaerobic to aerobic, resulting in diverse soil food web structure in the rice and wheat phases [12,13]. During the rice growing season, the field is flooded and under anaerobic conditions for 3–4 months, then drained [14]. Under paddy rice, soil microbial communities are dominated by strictly anaerobic fungi, bacteria (e.g. *Colstridium* spp., *Streptococcus* spp., *Staphylococcus* spp.) and archaea (e.g. methanogens) [15]. Bacterial populations are generally larger than fungal populations, but the soil organic matter decomposition rate is slow due to the low oxygen content [16]. The nematode community will include species that prefer anaerobic environments such as the plant-feeding nematode *Hirschmanniella* [17]. In contrast, upland wheat is rainfed and soils drain between rainfall events, providing an aerobic environment that is suitable for the activity and growth of most bacteria and fungi, e.g. carbon mineralization was ~10 times faster under aerobic than anaerobic conditions [18]. This is expected to provide ample food resources for bacterial-feeding and fungal-feeding nematodes, including the fungal-feeding nematode *Filenchus* whose population was larger in soils having an elevated O_2 concentration, i.e., 200 ppm greater than the ambient O_2 level [17].

The objective of this study was to determine if the soil nematode community responded to fertilization consistently in both phases of a paddy rice–upland wheat system. We hypothesized that (1) more bacterial- and fungal-feeding nematodes will exist in the upland wheat phase than paddy rice phase, and (2) straw addition will support greater abundance of fungal-feeding nematodes, whereas manure addition will favor more plant-feeding nematodes. These hypothesis were evaluated for five fertilizer treatments during a three year period (2011–2013) in a paddy rice–upland wheat system in southeast China.

2. Materials and methods

2.1. Site and experimental design

We conducted the study at Jintan, Jiangsu Province, China (31°39′N, 119°28′E), where double-cropping of summer rice (*Oryza sativa* L.) and winter wheat (*Triticum aestivum* L.) is a common agricultural practice on 80% of farms. This region has a humid subtropical climate (Köppen climate classification) with average annual precipitation is of 1063.6 mm. The mean summer temperature of 25 °C, ranging from 18 to 30 °C, occurs during the rice growing season and the mean winter temperature during wheat growing season is 9 °C, with a range of 2–20 °C. Water regime management is obviously different between the two phases. During the rice growing season, the field is flooded and under anaerobic conditions for about 130 days, then drained for 5–10 days. The upland wheat planted in the same field is rainfed and under aerobic conditions during the wheat growing season (about 140 days). Soil in the experimental field is classified as clay loam texture (USDA soil classification). Initial soil analysis was 13.5 g organic C kg^{-1}, 1.6 g total N kg^{-1}, 18.0 mg available P kg^{-1}, 56.4 mg available K kg^{-1} and pH of 7.3.

The fertilization experiment was established in November 2010. We set up twenty plots (5m × 8 m per plot) and randomly assigned five fertilizer treatments in four blocks (=four replicates per treatment). Every plot was separated by 0.15 m concrete buffers on both sides and there was a 1.5 m lane between blocks. Five fertilization treatments were: no fertilizer (CK), chemical fertilizer (CF), compound pig manure-chemical fertilizer (MCF), straw + chemical fertilizer (SCF), and pig manure + straw + 50% chemical fertilizer (MSCF). The CF and SCF treatments received 240 kg N ha^{-1} from urea, 120 kg P_2O_5 ha^{-1} from triple superphosphate and 100 kg K_2O ha^{-1} from muriate of potash, while the MSCF treatment received 120 kg N ha^{-1} from urea, 60 kg P_2O_5 ha^{-1} from triple superphosphate and 50 kg K_2O ha^{-1} from muriate of potash, as summarized in Table 1. The compound fertilizer used for the MCF treatment contained 12.2% N, 2% P and 2% K with 16.1% organic matter and moisture content of 19.3%. As MCF was applied at a rate of 240 kg MCF ha^{-1} (wet weight basis), this resulted in an input of 27 kg N ha^{-1}, 10 kg P_2O_5 ha^{-1} and 5.2 kg K_2O ha^{-1} as well as 35 kg organic matter ha^{-1} (Table 1). Straw in the SCF and MSCF treatments either contained 0.63% N, 0.11% P, 0.85% K, 78.6% organic matter and 33.1% moisture when applied as 18 t rice straw ha^{-1} (wet weight basis) in the wheat phase, while wheat straw with 0.52% N, 0.11% P, 1.07% K, 82.6% organic matter and 30.7% moisture was applied at 11 t wheat straw ha^{-1} (wet weight basis) in the rice phase. Thus, the SCF and MSCF treatments received an additional NPK input of 76 kg N ha^{-1}, 30 kg P_2O_5 ha^{-1} and 123 kg K_2O ha^{-1} plus 943 kg organic matter ha^{-1} in the wheat phase, while received an additional NPK input of 40 kg N ha^{-1}, 19 kg P_2O_5 ha^{-1} and 98 kg K_2O ha^{-1} plus 628 kg organic matter ha^{-1} in the rice phase. In the MSCF treatment, pig manure containing 2.3% N, 1.3% P, 1.0% K and 45.4% organic matter with moisture content of 29.1% was applied at 400 kg pig manure ha^{-1} (wet weight basis). Thus, the MSCF treatment received an additional NPK input of 6.5 kg N ha^{-1}, 8.5 kg P_2O_5 ha^{-1} and 3.4 kg K_2O ha^{-1} plus 128.8 kg organic matter ha^{-1}. Total NPK fertilizer and organic matter inputs applied in two phases are summarized in Table 1.

Fertilizer treatments were applied in both rice and wheat growing seasons. The P_2O_5, K_2O, straw and pig manure were applied as basal fertilizers 3–5 d before planting summer rice in June (harvested in late October) and 3–5 d before planting winter wheat in November (harvested in late May). The total rice straw was returned to soil before planting wheat, while total wheat straw was returned to soil before planting rice. After broadcasting the basal fertilizers uniformly across the plot area, they were incorporated to a depth of 15–20 cm with a tilling machine within 24 h of application. The urea-N fertilizer application was split into three equal amounts and applied before planting (broadcast and incorporated with the basal fertilizers), at the tillering stage (broadcast uniformly across the plot area) and at the panicle stage (broadcast uniformly across the plot area).