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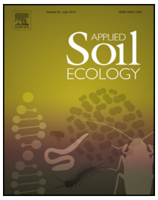

Vegetable yields and soil biochemical properties as influenced by fertilization in Southern China

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ABSTRACT

Nitrogen (N) fertilizer is commonly excessive in vegetable production, which greatly increases the risk of N loss and may eventually lead to the contamination of adjacent surface and ground water bodies. We assessed the effects of different fertilizer treatments on vegetable yields and soil biochemical properties, with the aim to develop best fertilizer management strategy for vegetable production. A five-year study (from 2008 to 2012) was conducted on a vegetable field in Jiangsu Province, southern China, with six fertilizer treatments: no fertilizer (control; CK), mineral fertilizer (NPK), chicken manure (OM), manure combined with mineral N fertilizer (OPT), OPT plus additional N fertilizer (OPT + N) and OPT plus additional phosphorus (P) fertilizer (OPT + P). Vegetable yields were measured each year, multiple soil (0–20 cm) chemical and biochemical characteristics were analyzed at the end of the study. Moreover, the soil ammonia-oxidizing microbial community structure was analyzed based on the PCR-DGGE method. Results showed that all fertilizer treatments produced higher economic vegetable yields than CK, with the highest yields in OPT. Combined application of manure and mineral fertilizer (OPT, OPT + N and OPT + P) produced higher yields than OM and NPK that had similar yields. All treatments with manure promoted soil carbon, N and P levels and reduced the potential of soil acidity. The OPT + P treatment performed best in enhancing soil fertility, which, for example, increased the concentrations of soil total-N, nitrate-N and microbial biomass N by 15.8%, 51.0% and 53.5%, respectively, compared to OPT. In addition, the OPT + P treatment had the highest abundance and diversity of ammonia-oxidizing archaea (AOA), which was positively correlated to the soil ammonium-N and nitrate-N concentrations. Possibly, the additional P in OPT + P could stimulate soil microbial activity, with positive implications for N fertility. However, the OPT + P treatment may also increase the risk of N loss due to an increasing soil nitrate-N, making it a less desirable fertilizer management strategy. In conclusion, the combined application of organic and chemical fertilizers without additional N or P (OPT) is suggested to be the best fertilizer management strategy that can improve soil fertility and vegetable yields, and meanwhile reduces the potential of N loss from soil.

1. Introduction

Terrestrial vegetable production is increasing in both the tropical and subtropical regions of the world (FAO, 2010), and it has become one major source of income for many farmers (Chen et al., 2013). In China, a total of 57.4×10^3 million tons of vegetables and cucurbits were produced on 2.5×10^3 million hectares of lands in 2013, which accounted for 52% of the world's production of vegetables and cucurbits (FAO, 2013). Commonly, large and excessive amounts of mineral nitrogen (N) fertilizers are used to obtain high yields of vegetables in China (Zhu and Chen, 2002). As a result, the N recovery of harvested vegetables has been only 20% of

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the applied N in many vegetable fields (Huang et al., 2006). The overuse of N fertilizers has risen several concerns over sustainability of vegetable production. These include the costs of fertilizer inputs associated with the low N use efficiencies and degradation of the environment such as greenhouse gas emissions (Zhang et al., 2013) and water pollution by nitrate leaching and runoff losses (Huang et al., 2006; Ju et al., 2009). The use of organic fertilizers such as animal manure has been strongly recommended in many areas of China, as a replacement for some or all mineral fertilizers. Previous work has well demonstrated benefits of using organic manures compared to mineral fertilizers. The benefits include mitigation of global warming (Yang et al., 2015) and reduction of NO_3^- pollution to the surface and ground waters (Meng et al., 2005). Application of organic fertilizers can also improve crop yields (Liu et al., 2016; Diacono and Montemurro, 2010), and enhance long-term soil fertility by increasing soil organic carbon (SOC), total N (TN), total phosphorus (TP) and dissolved organic carbon (DOC) (Liang et al., 2011; Zhang et al., 2016; Xi et al., 2016). Moreover, organic fertilizers are found to increase soil microbial activities by up to 20% as compared to inorganic fertilizers (González et al., 2010; Li et al., 2015), probably by supplying nutrients for soil microorganisms (Liu et al., 2010).

Fertilization can have comprehensive effects on soil microbial processes, key microbial community structures and N availability (Chivenge et al., 2010), which are crucial to determine soil fertility, crop production and N losses to the environment (Shen et al., 2013; Lazcano et al., 2013). Nitrogen transformation and availability strongly depend on the processes of mineralization (including ammonification and nitrification) and immobilization (Zhang et al., 2012a). Most N in manure is present in organic forms and is not available for plant uptake without being mineralized to inorganic forms (NH_4^+ and NO_3^-) (Urquiaga and Zapata, 2000).

Several studies have demonstrated that the gross N mineralization is significantly enhanced by long-term applications of mineral and manure fertilizers (Zhang et al., 2012a; Abbasi and Khizar, 2012). Abbasi and Khizar (2012) observed that soil N mineralization was doubled after incubation with poultry manure compared to addition of chemical N fertilizer. It was considered that the organic fertilizers could stimulate the mineralization of labile organic N while the mineral N enhanced the mineralization of recalcitrant organic N (Zhang et al., 2012a). Moreover, P availability can also influence N mineralization, nitrification and denitrification process. Greater P availability is reported to increase N losses to water and air (Mori et al., 2010; Fisk et al., 2014; He and Dijkstra, 2015), especially in P-poor soils where nitrifiers and denitrifiers are more easily be stimulated by P addition (He and Dijkstra, 2015).

Ammonia oxidation, the conversion of N from ammonia to nitrite, is regarded as the rate-limiting step of nitrification in terrestrial ecosystems, and therefore is the central of the global N cycling (Kowalchuk and Stephen, 2001). Ammonia oxidation process is generally regarded to be driven by both ammonia-oxidizing archaea (AOA) and ammonia- oxidizing bacteria (AOB) (Chu et al., 2007). However, increasing evidences have demonstrated that AOA singly dominates N nitrification in acidic soil ecosystems (Gubry-Rangin et al., 2010; Yao et al., 2011), since the first report on Chinese paddy soils (Chen et al., 2008). Numerous reports have shown a significant influence of fertilization on soil microbial properties and community composition (Gu et al., 2009; Feng et al., 2015). Usually, addition of organic manure promotes abundance of soil microbial communities (He et al., 2007; Fan et al., 2011). This is mainly because that organic matters contain abundant and balanced nutrients (including organic C and inorganic salts) that are beneficial for the growth of microorganisms involved in N cycling (Chen et al., 2012).

One main objective of this study was to investigate the mid-term effects of different mineral and organic fertilizer treatments on vegetable yields, soil biochemical properties (pH, SOC, ammonium-*N*, nitrate-*N*, microbial biomass) and biological processes (soil respiration rate, mineralization and nitrification). Moreover, we analyzed how AOA community abundance and the diversity are related to soil properties, and examined how the relationships were affected by different fertilizer treatments. The results will contribute to the development of best fertilizer management strategies in vegetable production.

2. Materials and methods

2.1. Site description and experimental design

A five-year experiment (from 2008 to 2012), which featured the double cropping of rhizome leafy vegetables and fruit vegetables, was conducted in a well-drained field at Changzhou (31°30′N, 120°6′E), Jiangsu Province, southern China. The experimental site is located in a typical subtropical humid monsoon climate zone, with mean annual temperature of 14.9-16.2 °C, annual average precipitation of 1 086 mm (approximately 80% during February to August), and annual average evaporation of 1 000 mm. Annually, there are 230 days free of frost and over 2 000 h of sunshine. The site has a clay loam soil that is classified as yellow-brown paddy soil by Chinese soil classification, and Udalfs by USDA soil classification. Soil physical and chemical properties were determined for the upper soil layer (0–20 cm) at start of the field experiment in 2008. The soil had the following properties: bulk density = 1.12 g cm^{-3}, pH = 6.2, SOC = 11.8 g kg^{-1}, TN = 2.2 g kg^{-1}, ammonium-N (NH_4^+-N) = 382 mg kg^{-1}, nitrate-N (NO_3^--N) = 36 mg kg^{-1}, TP = 1.0 g kg^{-1}, plant available P (Olsen-P) = 105 mg kg^{-1} and available potassium (K) = 127 mg kg^{-1}.

In each experimental round of the double cropping, green vegetables (*Brassica chinensisvarchinensis*) were planted in late April or early May and harvested in late September, and eggplants (*Solanummelongena* L.) were planted in mid-October and harvested in mid-March next year. All vegetables are grown in the open field. The plantation was done without plastic film. All above-ground biomass were manually harvested and then separated as leaves (for green vegetable) or fruits (for eggplant), which were oven dried to constant weight. A randomized block design with six fertilization treatments and three replicated blocks (field plot size: 6 m × 3 m) was used. The treatments were: (1) control (CK) with no amendments; (2) mineral fertilizer treatment (NPK); (3) organic chicken manure treatment (OM); (4) manure combined with mineral fertilizer treatment (OPT); (5) OPT plus additional N fertilizer treatment (OPT + N); and (6) OPT plus additional P fertilizer treatment (OPT + P).

The chicken manure was collected from a chicken farm near the study site and composted by regular turning (2–3 times) over a 3-month period before application. The manure contained 13.4 g N kg^{-1}, 25.2 g P_2O_5 kg^{-1} and 14.8 g K_2O kg^{-1}, on a dry weight basis (the same below). All manure was applied as basal fertilizer, at a rate of 21 t ha^{-1} $year^{-1}$ in the OM treatment and 10.5 t ha^{-1} $year^{-1}$ in OPT, OPT + N and OPT + P. The basal N, P and K fertilizers were applied as the compound fertilizer (N-P_2O_5-K_2O = 15-15-15). The additional N and P fertilizer was provided with ammonium bicarbonate and calcium magnesium phosphate. In treatments without organic manure application, two thirds of the N was applied in the form of ammonium bicarbonate as a basal fertilizer and one third as topdressing for both green vegetables and eggplants. Both mineral and manure basal fertilizers were uniformly broadcast onto the soil surface and immediately incorporated into soil (0–20 cm depth) by plowing before sowing.