Catena 133 (2015) 293–302

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Assessing soil quality of gleyed paddy soils with different productivities in subtropical China

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ARTICLE INFO

Article history:
Received 10 October 2014
Received in revised form 26 April 2015
Accepted 29 May 2015
Available online 10 June 2015

Keywords:
Gleyed paddy soil
Soil quality
Minimum data set
PLFA
Soil quality index (SQI)

ABSTRACT

Objective: Gleyed paddy soil is a typical soil with low productivity, and gleization of paddy soil is a serious issue in subtropical China. A systematic evaluation of soil quality can facilitate improvements in soil fertility and productivity. However, research data on soil quality assessment of gleyed paddy soils remain limited. Our study was to quantify soil quality and assess the constraints limiting rice productivity of gleyed paddy fields.
Methodology: Based on the mean annual rice yield, gleyed paddy soils were divided into high (HPGS, >13,500 kg ha^{-1}), medium (MPGS, 11,250–13,500 kg ha^{-1}), and low productivity (LPGS, >11,250 kg ha^{-1}). Eighty-four soil samples were collected and analyzed for 28 soil parameters including physical, chemical, and biological properties. The 17 variables showing significant differences ($P \leq 0.05$) among HPGS, MPGS and LPGS were selected for principal component analysis.
Results: A minimum data set (MDS) was established with total nitrogen (TN), available K (AK), microbial biomass C, β-glucosidase, total bacteria and arbuscular mycorrhizal fungi, accounting for 88.0% of the quality variation among soils. Soil quality index (SQI) was also developed based on the MDS method, and HPGS, MPGS and LPGS received mean SQI scores of 0.87 ± 0.05, 0.73 ± 0.04, and 0.64 ± 0.05, respectively, thus ranking as HPGS > MPGS > LPGS.
Conclusion: Overall, HPGS showed relatively good soil quality and was characterized by high levels of nutrient availability, and enzymatic and microbial activities, but the opposite was true of LPGS. Lower levels of TN, AK and biological activities were considered as the major constraints limiting rice production in LPGS compared with HPGS. Our study area was seriously deficient in AK limiting crop production. Significant correlation between SQI and rice yield suggested that SQI may be a promising tool to integrate soil information and indicate the degree of soil quality for gleyed paddy soil in subtropical China and other paddy areas with similar soils.

1. Introduction

Food insecurity is an increasing problem of the 21st century due to limited and degraded soil resources, and meeting food demand remains a top priority in many developing countries such as China (Kong, 2014). Paddy soils occupy a vast area in subtropical China, and considerable amounts of gleization have occurred in those regions. Gleization of paddy soil is a primary type of soil degradation, and it poses a serious challenge to national food security (Zeng and Pan, 1997). Gleyed paddy soils are soils showing reduced conditions as a result of extended waterlogging or poor drainage. They cover about 4×10^6 ha, and are one the most important low-yield soil types in subtropical China. Improving their productivity is an important means for ensuring national food security, which remains challenged by various limiting factors. Numerous researchers have studied the characteristics of gleyed paddy soils and explored methods of improving production through various forms of field management (Li et al., 2010, 2013). Weak air circulation and toxicity of reduced substances have been determined to be the major limiting factors (Pan, 1996). Rational fertilization and paddy-upland rotation are considered as two effective measures to obtain high rice yields in gleyed paddy soils (Gong et al., 1990). Previous studies have reported that soil quality evaluation is crucial to design farming systems more effectively (Bastida et al., 2008; Tesfahunegn et al., 2011). Unfortunately, an improved knowledge involving current status of soil attributes remains limited for gleyed paddy soil.

Soil quality evaluation has received considerable attention in response to the increasing global emphasis on sustainable land use (Li et al., 2013). Selecting representative indicators is key to soil quality evaluation, which should involve all predominant physical, chemical and biological soil properties (Bhardwaj et al., 2011). Although soil biological properties have been increasingly used, many previous studies

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http://dx.doi.org/10.1016/j.catena.2015.05.029
0341-8162/

are still focused on evaluating soil quality status using physico-chemical properties (Bastida et al., 2008; Bonanomi et al., 2011; Lima et al., 2013).

Soil quality is complex and its proper evaluation requires determining a large number of properties (Boluda et al., 2014). Many soil scientists have agreed to establish a minimum data set (MDS) to reduce the analysis costs because of its capacity to adequately represent the total data set (Qi et al., 2009; Rahmanipour et al., 2014). Soil quality index (SQI) can help managers evaluate the positive and negative effects of their practices on sustainability (Bhaduri and Purakayastha, 2014) and integrate information from soil indicators into the management decision process (Mohanty et al., 2007). However, only a few researchers have used the obtained results to establish a SQI (Bastida et al., 2008). Although a causal relationship was observed between soil quality and crop yield (D'Hose et al., 2014), many previous studies have neither provided crop-yield data nor analyzed the relationship between SQI and yield (Andrews et al., 2002; Li et al., 2013), therefore, their results likely have little agronomical significance.

In our study, 28 indicators involving physical, chemical and biological properties were measured, and the objectives were to: (i) establish an MDS for soil quality evaluation; (ii) develop a SQI to quantify soil quality status; and (iii) identify the limiting factors associated with the crop productivity of gleyed paddy soils.

2. Material and methods

2.1. Study area

Eighty-four sampling sites were selected in Hunan and Jiangxi provinces. These study areas were situated in the central south subtropical zone, which is characterized by a warm climate and plentiful rainfall. During the rice growing season (April–November), the mean temperature, precipitation, and evapotranspiration in the sampling areas of Hunan Province are 22.6 °C, 1040 mm and 540 mm, respectively. Similar climate conditions are observed in the sampling areas of Jiangxi Province, which has a mean annual temperature of 23.6 °C, precipitation of 1150 mm and evapotranspiration of 580 mm. Most of those gleyed paddy soils are developed from quaternary red clay or river deposit, and planted double-harvest rice per year.

According to the mean annual rice yield over the past five years, the selected gleyed paddy fields were divided into high (>13,500 kg ha^{-1}, HPGS), medium (11,250–13,500 kg ha^{-1}, MPGS), and low productivity (<11,250 kg ha^{-1}, LPGS). Based on farmers' surveys, conventional fertilization focused on mineral fertilizers, and fertilizer types were $CO(NH_2)_2$, $Ca(H_2PO_4)_2$ and KCl for N, P, and K, respectively. Compound fertilizer was also widely used in the study areas. Similar fertilization was employed for early rice and late rice at the sampling locations. For each cropping season, mean rates of 180 kg N ha^{-1}, 100 kg P_2O_5 ha^{-1} and 130 kg K_2O ha^{-1} were applied to the HPGS and MPGS, and 120 kg N ha^{-1}, 90 kg P_2O_5 ha^{-1} and 75 kg K_2O ha^{-1} to the LPGS in the sampling areas of Jiangxi Province, and the mean rates of 165 kg N ha^{-1}, 90 kg P_2O_5 ha^{-1} and 120 kg K_2O ha^{-1} were applied to the HPGS and MPGS, and 120 kg N ha^{-1}, 80 kg P_2O_5 ha^{-1} and 75 kg K_2O ha^{-1} to the LPGS in the sampling areas of Hunan Province. Coupled basic fertilizer and once tillage were conducted before each cropping season, and the N, P, and K fertilizers were usually applied totally as basic fertilizer during soil tillage across the whole study area. Although there were small differences in fertilizer application, the sampling areas are considered typical gleyed paddy soil regions because of their similar weather conditions, cropping systems, agricultural management (i.e., fertilization, tillage regime) and productivity levels.

2.2. Soil sampling

Based on rural surveys and information provided by the local agricultural department, the distribution of the gleyed paddy soils and sampling sites was determined, and then soil samples were collected from 0 to 20 cm within soil plow layer before the transplantation of early rice (April–May). In each selected gleyed paddy field, ten cores (5.0 cm diameter) were collected randomly and well mixed to form a composite sample. A total of 84 composite soil samples were collected, and the HPGS, MPGS and LPGS had representative soil samples of 22, 21, and 41, respectively. A GPS Trimble Asset Surveyor (version 5.20) with submeter accuracy was used for recording the geo-referenced coordinates, and the geographic location of the sampling points is shown in Fig. 1. Considering the analytical costs, four typical locations, Ningxiang (112°26′E, 28°12′N), Yongan (113°18′E, 28°13′N), Nanchang (116°04′E, 28°49′N), and Yongxiu (115°45′E, 29°06′N), were selected and each typical location indicates a regional scale in our study. In each typical region, soil sampling sites were determined based on rural surveys and information provided by the local agricultural department, and three soil samples alike three duplicates of each treatment were collected to represent each productivity class of gleyed paddy soil. In this way, a total of 36 soil samples were used for analyzing soil enzymatic activity and microbial community. In each typical location, three soil samples were collected to represent each productivity class of gleyed paddy soil. The field moist soil was divided into two subsamples. One subsample was immediately put into a valve bag avoiding contact with O_2 and analyzed for soil reduced substances within 3 days. The other subsample was also immediately transported to the laboratory, air-dried at room temperature for physical and chemical analyses, and stored at 4 °C for biochemical analysis or freeze-dried prior to storage at −18 °C for phospholipid fatty acid (PLFA) analysis.

2.3. Soil analyses

Soil aggregate stability (SAS) was measured using the wet sieving method (Beare and Bruce, 1993). Available phosphorus (AP) was determined using the method described by Olsen and Sommers (1982). Soil texture, bulk density (BD), total nitrogen (TN), alkali-hydrolyzable nitrogen (AN), soil organic matter (SOM), pH (soil/water 1:2.5), available potassium (AK), available zinc (AZn, 0.01 M hydrochloric acid extraction), available silicon (ASi, 0.025 M citric acid extraction), and cation exchange capacity (CEC, 1.0 M ammonium acetate extraction) were determined following the procedures described by Page et al. (1982). Total reduced substances (TRS), Fe^{2+} and Mn^{2+} were measured using the methods described by Liu and Yu (1962).

The activities of β-glucosidase and dehydrogenase were measured as described by Moeskops et al. (2010), and urease and acid phosphatase were determined as described by Tabatabai (1994).

Microbial biomass C and N were analyzed using the chloroform fumigation–incubation method and determined as described by Vance et al. (1987) and Shen et al. (1984), respectively.

Microbial community structure was determined using PLFA analysis as described by Wu et al. (2009). Concentrations of PLFAs were calculated as nmol g^{-1} and mol%. PLFA bio-indicators were selected according to the procedure of Moeskops et al. (2010), using only the PLFAs clearly identified by GC-FID: fatty acids iC15:0, aC15:0, iC16:0, iC17:0 and aC17:0 were used as biomarkers for Gram-positive bacteria (G+) and C16:1ω7c, C18:1ω7c and cyC17:0 for Gram-negative bacteria (G−). The sum of G+, G−, C:15, C17:0 and cyC19:0ω11,12c was assumed to represent the total bacterial community, and the sum of 10MeC16:0 and 10MeC18:0 was regarded as an indicator of actinomycetes. The fatty acids C18:2ω6,9c and C16:1ω5c were used as biomarkers for fungi and arbuscular mycorrhizal fungi (AMF), respectively.

2.4. Soil quality assessment

2.4.1. Selecting the minimum data set

All parameters were tested using one-way analysis of variance and the differences among means were analyzed using Tukey's honestly significant difference test at the probability level (P) of 0.05. Only variables with significant differences ($P < 0.05$) were chosen for PCA, and only