

DOI:10.11686/cyxb2024161

http://cyxb.magtech.com.cn

宁建凤, 陈勇, 姚建武, 等. 珠三角赤红壤常年连作菜地土壤磷库特征. 草业学报, 2025, 34(2): 133-148.

NING Jian-feng, CHEN Yong, YAO Jian-wu, et al. Characteristics of the soil phosphorus pool in continuously cultivated vegetable fields in the latosolic red soil zone of the Pearl River Delta. Acta Prataculturae Sinica, 2025, 34(2): 133-148.

珠三角赤红壤常年连作菜地土壤磷库特征

宁建凤*, 陈勇, 姚建武, 梁紫薇, 曾瑞锟, 王荣辉, 李彤

(广东省农业科学院农业资源与环境研究所, 农业部南方植物营养与肥料重点实验室, 广东省养分资源循环利用与耕地保育重点实验室, 广东省农业面源污染监测评估与防控工程技术研究中心, 广东广州 510640)

摘要:磷既是作物营养必需元素也是重要面源污染因子, 研究集约化菜地土壤磷库特征, 为有针对性地制定菜地磷养分管理措施, 降低菜地磷素面源污染风险提供依据。以珠三角地区(广州、江门、肇庆、惠州等地)赤红壤常年菜地系统为研究对象, 共采集89份城郊菜地土壤样品, 采用修正的Hedley磷库分级法分析土壤磷组分, 探明土壤性质与磷库相关性。赤红壤菜地土壤磷库以无机磷(Pi)为主要赋存形态, 无机磷在磷库占比达88%, 有机磷(Po)、残余磷在磷库占比均较低, 分别为8.1%、3.9%。菜地土壤无机磷含量为1176.78 mg·kg⁻¹, 远高于有机磷(109.03 mg·kg⁻¹)和残余磷含量(52.19 mg·kg⁻¹)。无机磷库中, H₂O-Pi、NaHCO₃-Pi、NaOH-Pi、稀HCl-Pi、浓HCl-Pi含量分别为46.35 mg·kg⁻¹、264.64 mg·kg⁻¹、427.45 mg·kg⁻¹、274.82 mg·kg⁻¹、163.52 mg·kg⁻¹, 在总磷中相应占比分别为3.32%、20.74%、31.29%、16.32%、14.13%。有机磷库中, NaHCO₃-Po、NaOH-Po、浓HCl-Po含量分别为27.24 mg·kg⁻¹、62.35 mg·kg⁻¹、19.44 mg·kg⁻¹, 占总磷比例依次为2.33%、5.70%、1.56%。NaOH提取磷(NaOH-P)在菜地无机磷库、有机磷库中均占主导地位。从土壤磷活性角度分析, 活性磷、中等活性磷、稳定性磷含量分别为338.23 mg·kg⁻¹、764.62 mg·kg⁻¹、235.15 mg·kg⁻¹, 在总磷中相应占比分别为25.3%、57.1%、17.6%。几乎全部89个样点土壤活性磷与中等活性磷之和在总磷库占比均超过50%。土壤有机质、全氮、碱解氮、速效钾、阳离子交换量(CEC)均与活性磷、中等活性磷含量呈显著正相关, 且存在浓度效应。赤红壤菜地土壤总体上磷含量丰富、有效性高。施肥、耕作管理等人活动及赤红壤特性共同影响土壤磷库形成。考虑到赤红壤区的强降水气候特征, 常年菜地磷素面源污染风险大, 应注意通过合理施肥降低磷的污染风险。

关键词:赤红壤菜地; Hedley磷库分级法; 无机磷组分; 有机磷组分; 磷有效性

Characteristics of the soil phosphorus pool in continuously cultivated vegetable fields in the latosolic red soil zone of the Pearl River Delta

NING Jian-feng*, CHEN Yong, YAO Jian-wu, LIANG Zi-wei, ZENG Rui-kun, WANG Rong-hui, LI Tong
Institute of Agricultural Resources and Environment, Guangdong Academy of Agricultural Sciences, Key Laboratory of Plant Nutrition and Fertilizer in South Region, Ministry of Agriculture, Guangdong Key Laboratory of Nutrient Cycling and Farmland Conservation, Guangdong Engineering Research Center for Monitoring and Prevention of Agricultural Non-point Source Pollution, Guangzhou 510640, China

Abstract: Phosphorus (P) is an essential nutrient for crops, and is a key factor that is monitored in the control of non-point pollution. It is important to clarify the characteristics of the soil P pool to devise strategies to manage P levels

收稿日期: 2024-04-30; 改回日期: 2024-06-14

基金项目: 国家自然科学基金项目(编号31701996), 广东省科技计划项目(编号2021B1212050019)和广东省农业科学院低碳中心与碳中和研究中心项目(编号XTXM202204)资助。

作者简介: 宁建凤(1978-), 女, 河北邯郸人, 博士, 研究员。E-mail: Jianfengning@gdaas.cn

* 通信作者 Corresponding author. E-mail: Jianfengning@gdaas.cn

and reduce P-related non-point pollution in intensively cultivated vegetable fields. In this study, we determined the characteristics of the soil P pool in the perennial vegetable fields in the latosolic red soil zone of the Pearl River Delta. A total of 89 soil samples were collected from the surface layer (0–20 cm) of vegetable fields located in the suburbs of Guangzhou, Jiangmen, Zhaoqing, and Huizhou. The composition of the soil P pool in the samples was determined using a modified Hedley method. Correlation analyses were conducted to reveal relationships between soil properties and the P pool. The results show that the proportions of inorganic P (Pi), organic P (Po), and residual P in the soil P pool were 88%, 8.1% and 3.9%, respectively, indicating that Pi was the dominant form in the soil P pool. The concentrations of these forms were as follows: Pi (1176.78 mg·kg⁻¹), Po (109.03 mg·kg⁻¹), and residual P (52.19 mg·kg⁻¹). The Pi pool consisted of several fractions, namely H₂O-Pi, NaHCO₃-Pi, NaOH-Pi, Dli HCl-Pi, and Con HCl-Pi, with concentrations of 46.35 mg·kg⁻¹, 264.64 mg·kg⁻¹, 427.45 mg·kg⁻¹, 274.82 mg·kg⁻¹, 163.52 mg·kg⁻¹, respectively; and proportions of 3.32%, 20.74%, 31.29%, 16.32%, and 14.13%, respectively, in the total P pool. The fractions in the Po pool were NaHCO₃-Po, NaOH-Po, and Con HCl-Po, with concentrations of 27.24 mg·kg⁻¹, 62.35 mg·kg⁻¹, and 19.44 mg·kg⁻¹, respectively; and proportions of 2.33%, 5.70%, and 1.56%, respectively, in the total P pool. The dominant form in both the Po and Pi pools was NaOH-P, specifically NaOH-Pi in the Pi pool and NaOH-Po in the Po pool. In terms of soil P availability, the concentrations of labile P, moderately labile P, and recalcitrant P were 338.23 mg·kg⁻¹, 764.62 mg·kg⁻¹, and 235.15 mg·kg⁻¹, respectively. The proportions of labile P, moderately labile P, and recalcitrant P in the total P pool were 25.3%, 57.1%, and 17.6%, respectively. The sum of labile P and moderately labile P accounted for more than half of the total P pool in almost all the 89 soil samples, suggesting that labile P and moderately labile P were the main P types in the soil. On the whole, the soil in the perennial vegetable fields in the latosolic red soil zone was rich in P in highly available forms. Significant positive correlations and concentration effects were detected between soil properties (organic matter, total nitrogen, available nitrogen, available potassium, cation exchange capacity) and labile P and moderately labile P contents. The soil P pool accumulates *via* anthropogenic activities i. e. fertilization and cultivation, and is also affected by the soil's intrinsic properties. Considering the climate characteristics in the Pearl River Delta, including heavy rainfall, the application of P nutrient management strategies is suggested to reduce the risks of P pollution in vegetable field soil.

Key words: vegetable field in latosolic red soil zone; Hedley phosphorus fractionation; inorganic phosphorus fractions; organic phosphorus fractions; phosphorus availability

磷(phosphorus, P)是限制作物生长及产量提高的必需营养元素之一。磷矿作为生产磷肥的主要原料,是不可再生型资源,目前全球磷矿储量将在50~100年内被耗竭^[1]。然而,磷肥不合理施用导致农田土壤磷素大量盈余。近40年来,磷肥在我国农业生产中呈大量持续施用发展态势^[2]。据报道,2010年我国农田年均磷盈余水平为24 kg·hm⁻²,远高于全球生态系统安全阈值(年均6.9 kg·hm⁻²)^[3]。我国广东地区农田土壤磷累积速度明显高于全国平均水平,1984–2010年间全省土壤有效磷含量增长了3倍,有效磷年均增加1.2 mg·kg⁻¹^[4]。诸多研究表明,磷在农田土壤大量累积不同程度增加了地表水环境污染风险^[5–6]。常年菜地是广东省主要种植系统之一,2021年广东省蔬菜播种面积为139.23×10⁴ hm²,占农作物总播种面积的31%^[7]。蔬菜由于种植效益高,超量不合理施肥现象十分普遍,探明赤红壤区常年菜地土壤磷库特征,对于蔬菜磷养分优化管理及降低菜地磷素面源污染风险至关重要。

磷在土壤中赋存形态决定其溶解度,进而影响其生物有效性。土壤中,磷有效性通常采用化学浸提剂提取的有效磷来表征,并据此确定作物需磷水平^[8]。然而,目前化学试剂如NH₄F仅提取到无机磷库中小部分有效磷,忽略了有机磷库中潜在可利用性磷^[9]。Hedley等^[10]开发出兼顾土壤有机、无机磷的磷形态分级方法,针对各形态磷素有比较明确的有效性意义。Hedley等^[10]和Cross等^[11]磷素分级体系及其修正方法为评估磷库大小及各磷组分

的生物有效性提供了科学依据,是目前公认的较合理且应用广泛的磷分级方法^[12]。近年来,国内外针对农田^[13]、园地^[14]、草地^[15]、林地^[16]、湿地^[17]等不同土地利用类型的土壤磷库以及磷组分对耕作管理、土地利用方式变化、土地退化等的响应开展了大量研究,土壤磷组分总体呈现出时空变异性大、区域性特征明显、影响因素多样化等特点^[18-20]。

赤红壤是广东省地带性土壤^[21],富含铁铝氧化物,是典型高固磷土壤类型^[22]。热带亚热带季风气候充足的水、热资源,使赤红壤区常年菜地系统在耕作施肥、农艺管理等方面呈现出典型的区域性特征,如多茬连作、周年生产、肥料用量大、施肥频繁、集约化程度高等^[23],土壤有效磷含量处于极丰富水平^[24]。目前,尚未有基于土壤磷素分级法的赤红壤区常年菜地土壤磷库现状的报道。以赤红壤常年菜地为研究对象,摸清土壤磷储量特征,阐明磷组分含量及赋存比例,为客观评价常年菜地耕作、施肥管理的科学性提供数据支撑,同时为今后本地区菜地土壤磷养分时空变化对比、评价提供基础数据,助力区域耕地质量保护与地力提升。

1 材料与方法

1.1 研究区概况

研究区位于广东省珠三角地区的广州、惠州、肇庆、江门等地的城郊常年菜地,土壤类型为赤红壤。该研究区为亚热带季风气候,光、热和水资源丰富,且雨热同期,年内降水主要集中在4—9月,年均降水量1300~2200 mm,年均气温20~22℃^[21]。常年菜地单一类型蔬菜如叶菜、茄果类或者多种类型蔬菜常年轮作种植。2021年,广州、惠州、肇庆、江门4地的蔬菜播种面积分别为14.67万、12.40万、9.20万和7.47万hm²,分别占当年农作物播种总面积的70%、48%、25%和24%^[7]。

1.2 样品采集

研究区常年菜地共设置89个采样点,其中广州市、惠州市、肇庆市、江门市采样点分别为30、19、22和18个。2019年2—5月,采集常年菜地表层土壤(0~20 cm)样品(图1)。所采集的89个菜地样点中,全部为常年蔬菜连作菜地,蔬菜种植类型包括叶菜类、茄果类、豆角类、葱类,一种或多种类型蔬菜常年轮作种植,所有样点的蔬菜种植年限均在5年以上。土壤样品采集方法及研究区蔬菜种植情况详见文献^[24]。

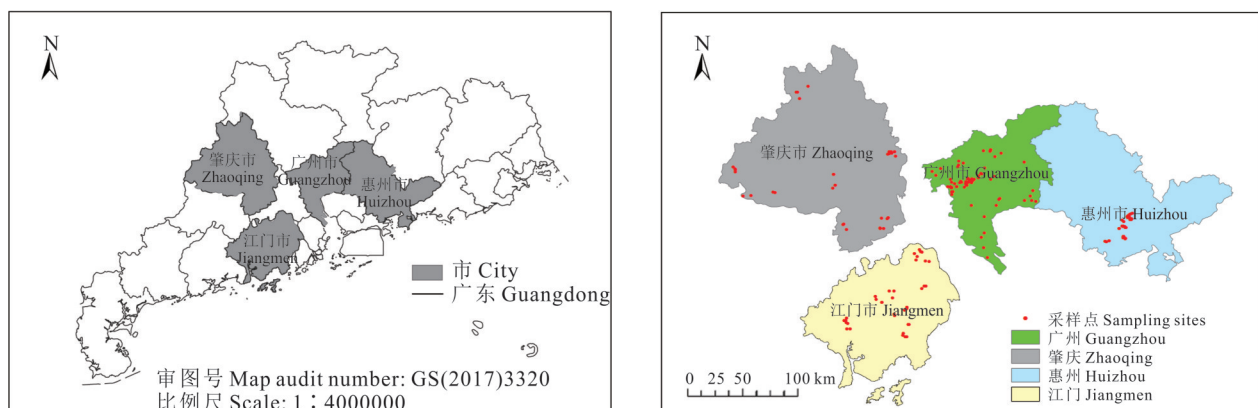


图1 菜地土壤样点分布

Fig. 1 Location of the study area and sampling sites

基于自然资源部标准地图服务网站GS(2017)3320号标准地图制作,底图边界无修改。Based on GS(2017)3320 standard map of the standard map service website of the Ministry of Natural Resources, the boundary of the base map is not modified.

1.3 供试土壤性质

所采集的菜地土壤样品,风干后制样,测定各项指标。土壤基础化学性质如表1^[24]所示。依据《中国土壤普查技术》^[25]土壤肥力指标分级标准,表1中,供试土壤pH呈微酸性,有机质含量为中等水平,阳离子交换量为中等偏下水平;全氮和全磷含量均属中等水平,全钾含量为中等偏下水平;碱解氮、速效钾含量属于丰富水平,有效磷

属于极丰富水平(92.1%的样品有效磷含量高于40 mg·kg⁻¹)。

1.4 土壤磷库分析、测定

土壤磷库分级及提取采用 Tiessen 等^[26]改进的 Hedley 等^[10]的方法。这种方法采用逐步增加提取剂强度分级提取不同活性磷组分。具体分析步骤为:称取0.5 g 过0.149 mm的风干土壤至50 mL离心管中,依次采用30 mL去离子水(H₂O-Pi)、0.5 mol·L⁻¹ NaHCO₃溶液(pH 8.5)(NaHCO₃-P)、0.1 mol·L⁻¹ NaOH溶液(NaOH-P)、1 mol·L⁻¹ HCl溶液(稀HCl-P, Dli HCl-P)和12 mol·L⁻¹ HCl溶液(浓HCl-P, Con HCl-P)进行提取。浸提过程中,加入每一步的浸提液后,室温下连续振荡16 h(200 r·min⁻¹),离心(10000 r·min⁻¹, 10 min, 0 °C),然后收集离心管上层清液并过0.45 μm滤膜,滤液用于测定无机磷(inorganic phosphorus, Pi)和全磷(total phosphorus, TP)含量。各部分提取液中Pi含量采用钼锑抗比色法^[27]测定,TP含量参照略微改动的 Tiessen 等^[26]的方法测定,即用过硫酸钾替代过硫酸铵,采用过硫酸钾氧化-钼锑抗比色法测定。提取液有机磷含量为全磷含量与无机磷含量的差值。分级提取的最后一步,即浓HCl提取后的残余土壤,采用浓HNO₃-HF-HClO₄消解-钼锑抗比色法^[28]测定,即为残余磷(residual phosphorus)。活性磷=H₂O-Pi+NaHCO₃-Pi+NaHCO₃-Po。中等活性磷=NaOH-Pi+NaOH-Po+稀HCl-Pi。稳定性磷=浓HCl-Pi+浓HCl-Po+残余磷。

表1 研究区常年菜地土壤基础理化性质

Table 1 Basic physicochemical properties of soil in perennial vegetable fields of the research area

指标 Parameters	pH	砂粒 (0.05~2.00 mm, %)	粉粒 (0.002~0.050 mm, %)	黏粒 (<0.002 mm, %)	阳离子交换量 CEC (cmol·kg ⁻¹)	有机质 OM (g·kg ⁻¹)
均值 Average	5.83	43.70	40.30	16.00	8.67	23.83
范围 Range	4.37~7.23	10.20~86.80	7.80~62.40	2.60~47.40	3.46~20.09	7.79~56.59
变异系数 CV (%)	11.20	38.40	30.89	49.66	40.20	42.00
指标 Parameters	全氮 TN (g·kg ⁻¹)	全磷 TP (g·kg ⁻¹)	全钾 TK (g·kg ⁻¹)	碱解氮 AN (mg·kg ⁻¹)	有效磷 AP (mg·kg ⁻¹)	速效钾 AK (mg·kg ⁻¹)
均值 Average	1.19	1.47	12.53	135.24	120.24	222.48
范围 Range	0.06~2.91	0.44~3.92	0.80~38.29	60.12~298.80	13.80~306.87	33.00~758.79
变异系数 CV (%)	57.10	50.10	51.50	35.30	21.80	51.80

CV: Coefficient of variations; CEC, Cation exchange capacity; OM, Organic matter; TN, Total nitrogen; TP, Total phosphorus; TK, Total potassium; AN, Available nitrogen; AP, Available phosphorus; AK, Available potassium. 下同 The same below.

1.5 数据处理与分析

采用软件 SAS 9.2 和 Origin 2023 进行数据处理、分析和作图。

2 结果与分析

2.1 土壤磷库组成

表2所示,常年菜地土壤无机磷(inorganic phosphorus, Pi)含量变化范围为314.63~3785.96 mg·kg⁻¹,均值为1176.78 mg·kg⁻¹。有机磷(organic phosphorus, Po)含量变化范围为31.46~367.41 mg·kg⁻¹,均值为109.03 mg·kg⁻¹。无机磷在土壤磷库的占比平均达88.0%,有机磷在土壤磷库中占比平均低于10%,均值为8.1%,且有机磷在土壤磷库的占比远低于相应无机磷比例。菜地土壤有机磷含量变异系数平均为41.81%,总体上低于无机磷含量变幅(变异系数57.79%)。常年菜地土壤中,残余磷含量为9.97~122.56 mg·kg⁻¹,均值为52.19 mg·kg⁻¹(表2)。土壤残余磷在土壤磷库中的占比均值为3.9%,残余磷含量均低于相应无机磷、有机磷含量。总体上,研究区菜地土壤残余磷含量均存在一定变幅,变异系数均值为43.04%。

2.2 无机磷组分

菜地土壤无机磷组分如图2所示。无机磷库中各组分H₂O-Pi、NaHCO₃-Pi、NaOH-Pi、稀HCl-Pi、浓HCl-Pi含量分别为3.09~144.32 mg·kg⁻¹、26.43~614.12 mg·kg⁻¹、83.74~1298.14 mg·kg⁻¹、6.05~1948.92 mg·kg⁻¹和

表 2 常年菜地土壤磷库组成

Table 2 Composition of phosphorus pool in soil of perennial vegetable fields

指标 Parameters	无机磷 Inorganic phosphorus (Pi)	有机磷 Organic phosphorus (Po)	残余磷 Residual phosphorus
均值 Average ($\text{mg}\cdot\text{kg}^{-1}$)	1176.78	109.03	52.19
范围 Range ($\text{mg}\cdot\text{kg}^{-1}$)	314.63~3785.96	31.46~367.41	9.97~122.56
变异系数 Coefficient of variations (CV, %)	57.79	41.81	43.04
占全磷比例均值 Average percentage in total (%)	88.0	8.1	3.9

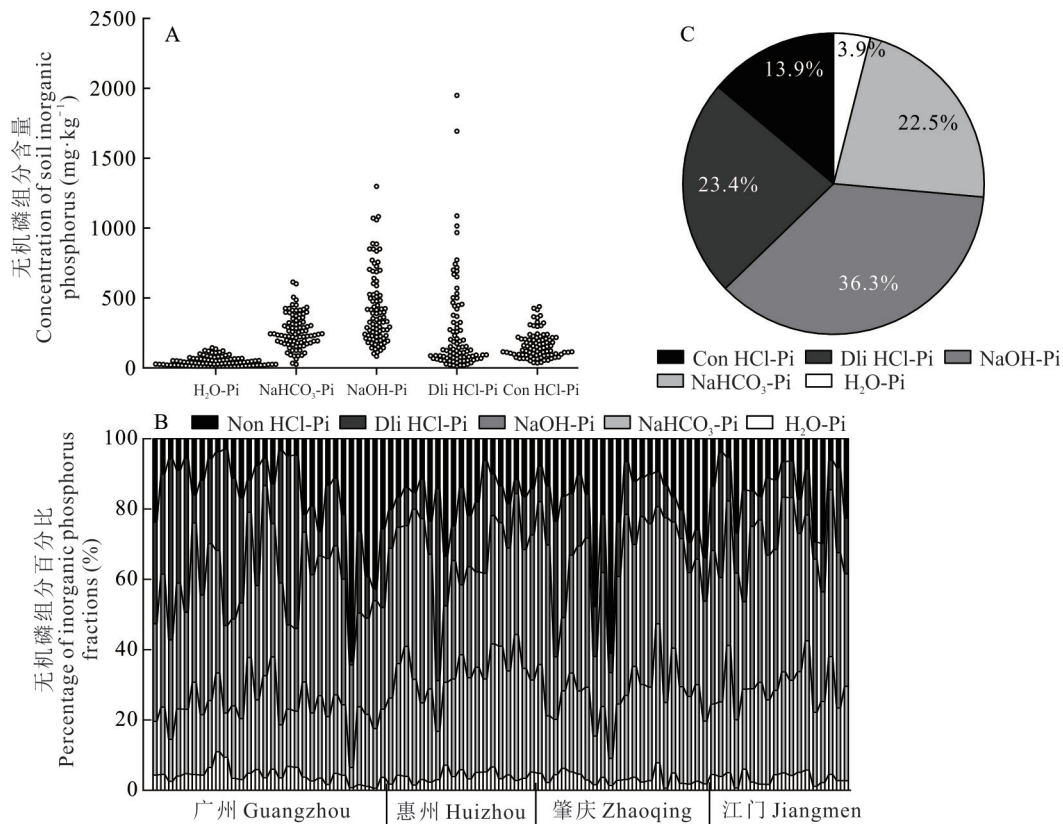


图 2 常年菜地无机磷组分含量及其所占百分比

Fig. 2 Concentration of inorganic phosphorus fractions and their percentage in the total inorganic P pool in soil of perennial vegetable fields

A: 无机磷组分含量 Concentration of inorganic phosphorus; B: 无机磷组分占无机磷库百分比 Percentage of inorganic phosphorus fraction in the total inorganic phosphorus pool; C: 无机磷组分占无机磷库百分比均值 Average percentage of inorganic phosphorus in the total inorganic phosphorus pool.

35.54~438.89 $\text{mg}\cdot\text{kg}^{-1}$, 相应的含量均值分别为 46.35 $\text{mg}\cdot\text{kg}^{-1}$ 、264.64 $\text{mg}\cdot\text{kg}^{-1}$ 、427.45 $\text{mg}\cdot\text{kg}^{-1}$ 、274.82 $\text{mg}\cdot\text{kg}^{-1}$ 、163.52 $\text{mg}\cdot\text{kg}^{-1}$ (图 2A)。不同样点各组分占无机磷库的百分比存在较大差异(图 2B), 其中, 稀 HCl-Pi 和浓 HCl-Pi 的占比变幅均较大, 变异系数分别为 67.0% 和 67.4%, 相应的占比分别为 1.05%~54.62% 和 3.0%~63.3%; 其次为 H_2O -Pi, 其在无机磷库的占比为 0.6%~11.0%, 变异系数为 49.9%; NaHCO_3 -Pi 和 NaOH-Pi 在无机磷的占比变化范围相对较小, 分别为 5.7%~41.5% 和 14.4%~54.04%, 相应的变异系数为 28.9% 和 23.8%(图 2B)。总体上, 所采集的 89 个样点, 土壤无机磷库中占比最高的组分为 NaOH-Pi(平均占比 36.3%); 其次为稀 HCl-Pi、 NaHCO_3 -Pi、浓 HCl-Pi(占比均值分别为 23.4%、22.5%、13.9%), H_2O -Pi 在无机磷的占比相对最低(3.9%)(图 2C)。在整个磷库中, 各无机磷占全磷比例为(表 3): H_2O -Pi 3.32%, NaHCO_3 -Pi 20.74%, NaOH-Pi 31.29%, 稀 HCl-Pi 16.32%, 浓 HCl-Pi 14.13%。

表3 常年菜地土壤无机磷组分占全磷比例

Table 3 Percentage of inorganic phosphorus fractions in the total phosphorus pool in soil of perennial vegetable fields (%)

指标 Parameters	H ₂ O-Pi	NaHCO ₃ -Pi	NaOH-Pi	Dli HCl-Pi	Con HCl-Pi
均值 Average	3.32	20.74	31.29	16.32	14.13
范围 Range	0.45~9.76	4.38~35.12	13.82~47.04	0.80~52.28	2.74~48.29
变异系数 Coefficient of variations (CV)	51.73	28.41	24.04	71.99	62.83

稀 HCl-P; Dli HCl-P; 浓 HCl-P; Con HCl-P.

2.3 有机磷组分

图3为常年菜地土壤有机磷组分含量及其在有机磷占比。有机磷库中,研究区菜地土壤 NaHCO₃-Po、NaOH-Po、浓 HCl-Po 含量分别为 2.01~81.3 mg·kg⁻¹、9.88~303.56 mg·kg⁻¹ 和 1.10~71.59 mg·kg⁻¹,相应的含量均值为 27.24 mg·kg⁻¹、62.35 mg·kg⁻¹、19.44 mg·kg⁻¹(图3A)。不同有机磷组分含量均存在较大变异,其中浓 HCl-Po 的变异系数最高,达 69.99%。有机磷库中,NaHCO₃-Po、NaOH-Po、浓 HCl-Po 3种有机磷组分的占比分别为 1.71%~61.62%、24.82%~82.62%、1.08%~60.97%(图3B)。总体上,有机磷库中 NaOH-Po 占比最高,为 57.2%;NaHCO₃-Po 和浓 HCl-Po 占比较为接近,分别为 25.0% 和 17.8%(图3C)。在总磷库中,NaHCO₃-Po 占比 2.33%,NaOH-Po 占比 5.70%、浓 HCl-Po 占比 1.56%(表4)。

2.4 土壤不同活性磷组分

以 H₂O、NaHCO₃ 提取的磷组分为活性磷,是磷库活性最高的部分^[29];NaOH 和稀 HCl 浸提的磷组分是中等活性磷^[26],浓盐酸提取的磷组分和残余磷主要由不溶性、稳定性的含磷化合物组成称为稳定性磷^[30]。表5中,不

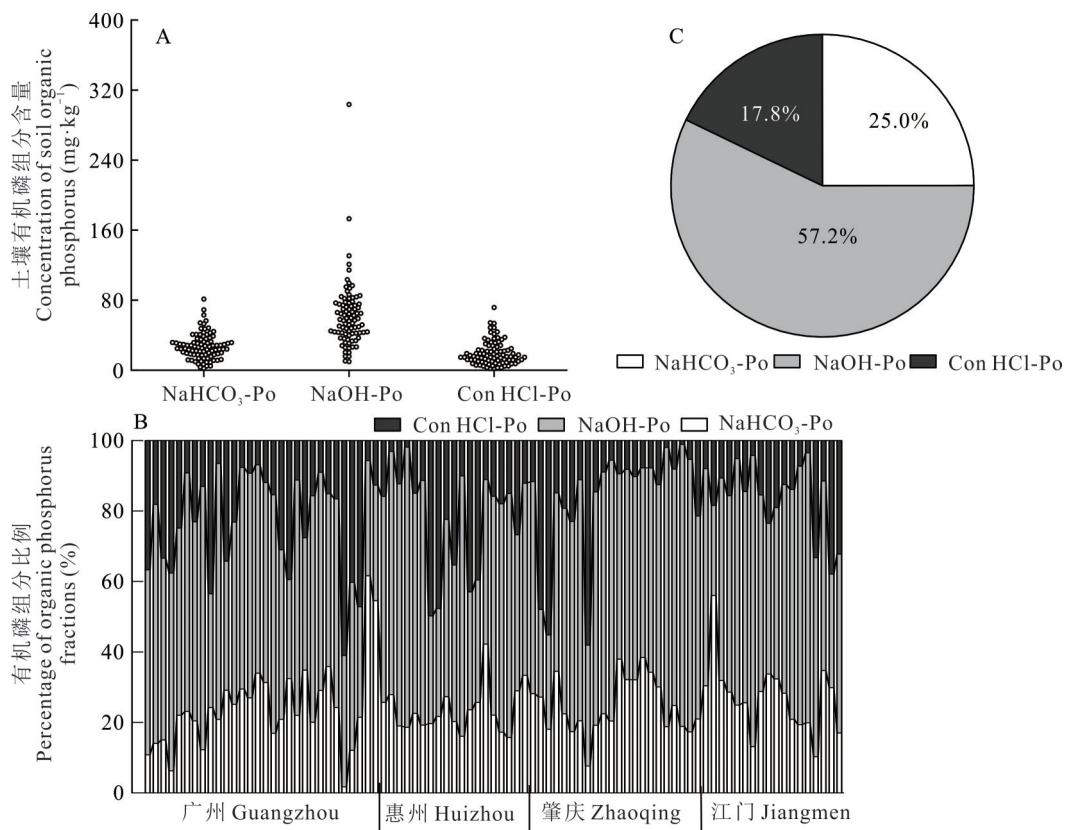


图3 常年菜地有机磷组分含量及其所占百分比

Fig. 3 Concentration of organic phosphorus fractions and their percentage in the total organic phosphorus pool in soil of perennial vegetable fields

A: 有机磷组分含量 Concentration of organic phosphorus; B: 有机磷组分占有有机磷库百分比 Percentage of organic phosphorus fraction in the total organic phosphorus pool; C: 有机磷组分占有有机磷库百分比均值 Average percentage of organic phosphorus in the total organic phosphorus pool.

同活性的磷组分中,中等活性磷含量最高(均值 $764.62 \text{ mg}\cdot\text{kg}^{-1}$),其次为活性磷含量(均值为 $338.23 \text{ mg}\cdot\text{kg}^{-1}$),稳定性磷含量(均值为 $235.15 \text{ mg}\cdot\text{kg}^{-1}$)低于前两种磷组分。不同活性的磷组分含量均存在一定的变幅,其中中等活性磷组分的含量变异系数最大,活性磷和稳定性磷的变幅较为接近。总体上,常年菜地土壤磷库中,中等活性磷占据主导地位(占比 57.1%),其次为活性磷(占比约为磷库 $1/4$),稳定性磷占比相对低于活性磷和中等活性磷。

表 4 常年菜地土壤有机磷组分占全磷比例

Table 4 Percentage of organic phosphorus fractions in the total phosphorus pool in soil of perennial vegetable fields (%)

指标 Parameters	$\text{NaHCO}_3\text{-Po}$	NaOH-Po	Con HCl-Po
均值 Average	2.33	5.70	1.56
范围 Range	0.22~9.20	0.54~27.38	0.19~9.45
变异系数 Coefficient of variations (CV)	59.31	70.19	76.12

表 5 常年菜地不同活性磷组分

Table 5 Fractions of phosphorus with different availability in soil of perennial vegetable fields

指标 Parameters	活性磷 Labile phosphorus	中等活性磷 Moderately labile phosphorus	稳定性磷 Recalcitrant phosphorus
均值 Average ($\text{mg}\cdot\text{kg}^{-1}$)	338.23	764.62	235.15
范围 Range ($\text{mg}\cdot\text{kg}^{-1}$)	39.49~766.11	158.72~3102.86	57.40~536.09
变异系数 Coefficient of variations (CV, %)	45.18	68.81	48.88
占全磷比例 Percentage (%)	25.3	57.1	17.6

2.4.1 土壤活性磷组分 菜地土壤 3 种活性磷组分中, $\text{H}_2\text{O-Pi}$ 、 $\text{NaHCO}_3\text{-Pi}$ 、 $\text{NaHCO}_3\text{-Po}$ 占比分别为 1.98% ~ 39.50% 、 52.90% ~ 91.17% 、 0.99% ~ 40.33% (图 4A), 平均占比分别为 13.7% 、 78.2% 、 8.1% (图 4B), 说明 $\text{NaHCO}_3\text{-Pi}$ 是土壤活性磷库的主要组分。

2.4.2 土壤中等活性磷组分 土壤中等活性磷中, NaOH-Pi 、 NaOH-Po 、稀 HCl-Pi 占比分别为 20.65% ~ 79.30% 、 1.01% ~ 45.86% 、 2.77% ~ 78.12% (图 5A), 相应占比均值为 55.9% 、 8.2% 、 35.9% (图 5B)。土壤中等活性磷库中, NaOH-Pi 是主要的磷组分, 其次为稀 HCl-Pi , NaOH-Po 占有一定比例, 但含量较低。

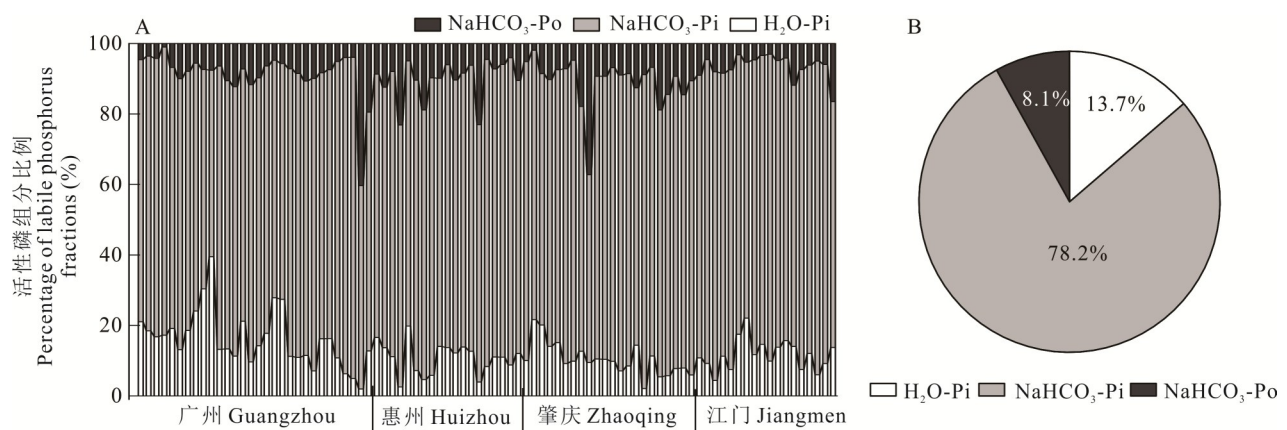


图 4 常年菜地活性磷组分占活性磷库百分比及其均值

Fig. 4 Percentage of labile phosphorus fraction in soil total labile phosphorus pool and their average in soil of the perennial vegetable fields

A: 活性磷组分占活性磷库百分比 Percentage of labile phosphorus fraction in the total labile phosphorus pool; B: 活性磷组分占活性磷库百分比均值 Average percentage of labile phosphorus in the total labile phosphorus pool.

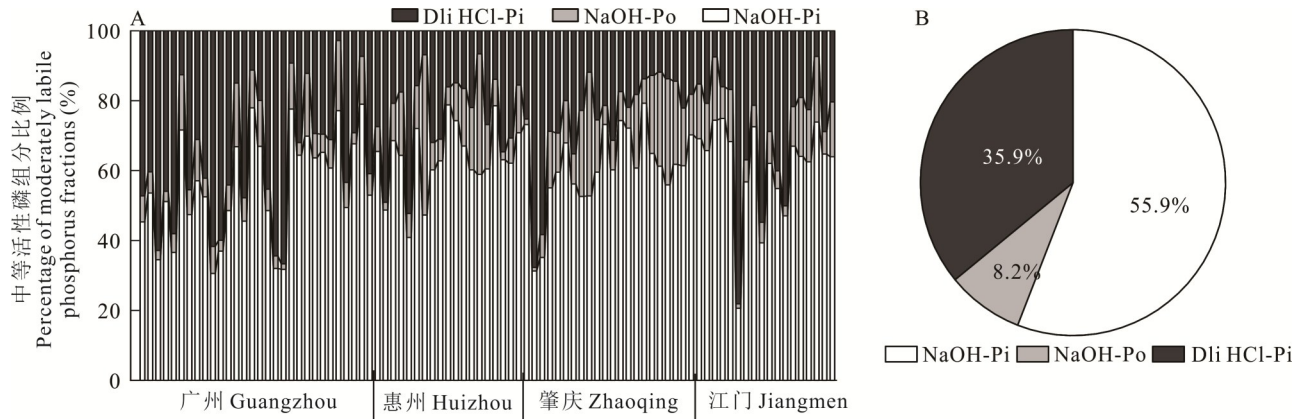


图5 常年菜地中等活性磷组分占中等活性磷库百分比及其均值

Fig. 5 Percentage of moderately labile phosphorus fractions in the total moderately labile phosphorus pool and their average in soil of the perennial vegetable fields

A: 中等活性磷组分占中等活性磷库百分比 Percentage of moderately labile phosphorus fractions in the total moderately labile phosphorus pool; B: 中等活性磷组分占中等活性磷库百分比均值 Average percentage of moderately labile phosphorus in the total moderately labile phosphorus pool.

2.4.3 土壤稳定性磷组分 菜地土壤稳定性磷中, 浓 HCl-Pi、浓 HCl-Po、残余磷占比分别为 38.40%~84.80%、0.67%~48.69%、9.68%~47.25%(图 6A), 相应的占比均值为 69.5%、8.3%、22.2%(图 6B)。土壤稳定性磷库中, 浓 HCl-Pi 是主要的磷组分, 其次为残余磷, 浓 HCl-Po 的占比相对较低。

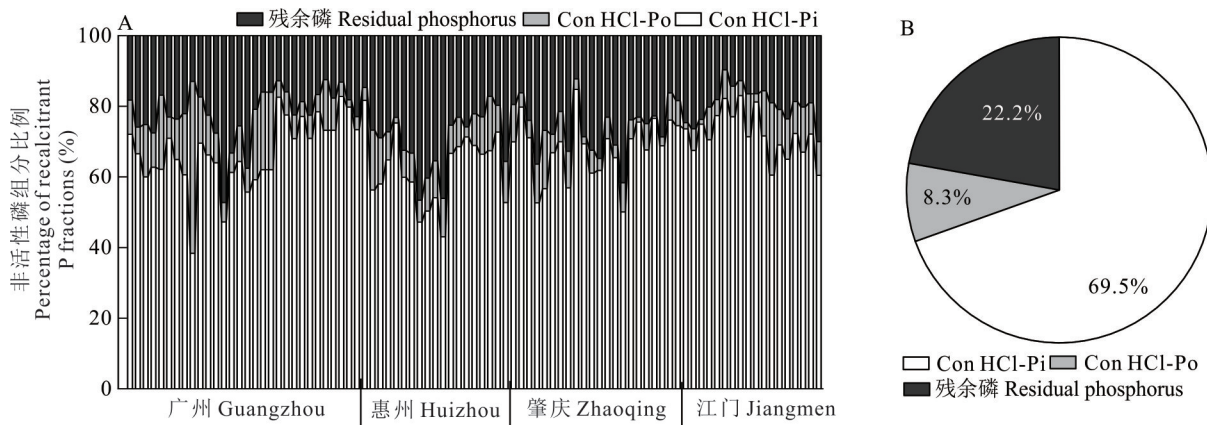


图6 常年菜地稳定性磷组分占稳定性磷库百分比及其均值

Fig. 6 Percentage of recalcitrant phosphorus fractions in the total recalcitrant P pool and their average in soil of the perennial vegetable fields

A, 稳定性磷组分占稳定性磷库百分比 Percentage of recalcitrant phosphorus fractions in the total recalcitrant phosphorus pool; B, 稳定性磷组分占稳定性磷库百分比均值 Average percentage of recalcitrant phosphorus in the total recalcitrant phosphorus pool.

2.5 磷库与土壤性质相关性

土壤活性磷、中等活性磷、稳定性磷含量与土壤性质相关性分析结果如图 7 所示。活性磷、中等活性磷含量与土壤有机质、阳离子交换量、全氮、碱解氮、速效钾等均呈显著或极显著正相关关系。土壤稳定性磷含量与阳离子交换量、全钾含量呈显著正相关。活性磷、中等活性磷、稳定性磷作为土壤全磷的组成部分, 其含量均与全磷含量呈显著或极显著正相关。活性磷、中等活性磷与土壤有效磷含量之间均存在极显著正相关关系, 稳定性磷与有效磷含量之间无显著相关性。

活性磷、中等活性磷具有较高的生物有效性。选择与土壤活性磷、中等活性磷含量显著相关的土壤指标, 即有机质 (organic matter, OM)、阳离子交换量 (cation exchange capacity, CEC)、全氮 (total nitrogen, TN)、碱解氮

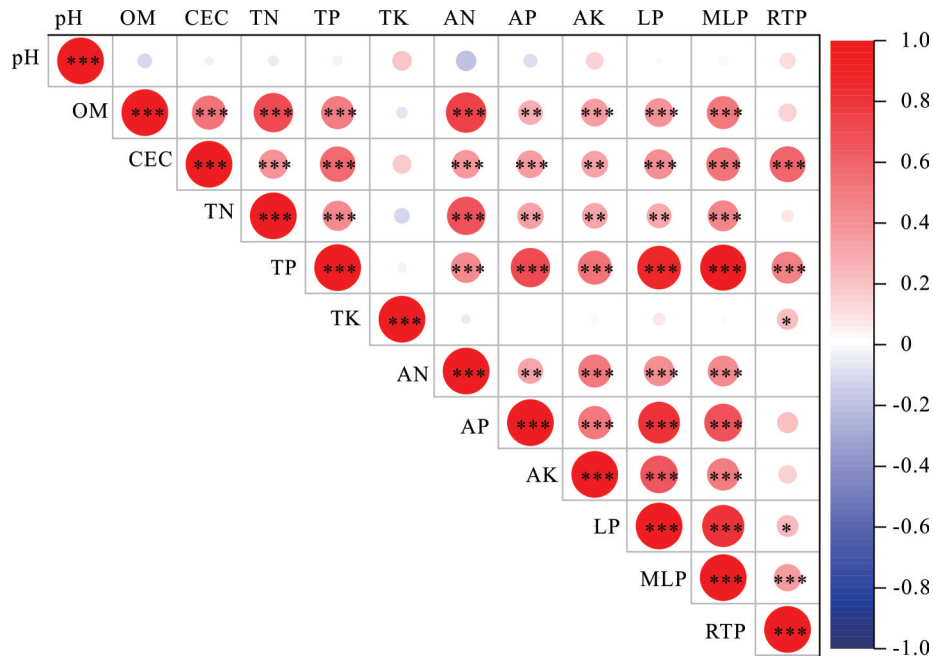


图 7 常年菜地土壤性质与磷库相关性

Fig. 7 Correlations between soil properties and phosphorus pool

* $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$. OM: 有机质 Organic matter; CEC: 阳离子交换量 Cation exchange capacity; TN: 全氮 Total nitrogen; TP: 全磷 Total phosphorus; TK: 全钾 Total potassium; AN: 碱解氮 Available nitrogen; AP: 有效磷 Available phosphorus; AK: 速效钾 Available potassium; LP: 活性磷 Labile phosphorus; MLP: 中等活性磷 Moderately labile phosphorus; RTP: 稳定性磷 Recalcitrant phosphorus.

(available nitrogen, AN)、速效钾 (available potassium, AK), 进一步分析不同活性的磷在各土壤指标分级条件下的含量分布特征 (图 8)。土壤各指标分级参照《中国土壤普查技术》^[25] 中养分分级标准进行。全部 89 个样点中, 仅 1 个样点的土壤 OM 含量低于 $10 \text{ g} \cdot \text{kg}^{-1}$, CEC 含量高于 $20 \text{ cmol} \cdot \text{kg}^{-1}$, 选择其余 88 个样点进行土壤 OM、CEC 不同含量分级条件下的数据分析。土壤 TN、AN、AK 含量为全部 89 个数据的分析结果。

图 8A 中, 80.9% 的样点土壤活性磷、中等活性磷分布在 $10 \sim 30 \text{ g} \cdot \text{kg}^{-1}$ 的 OM 含量范围内。活性磷、中等活性磷含量分别在土壤 OM 含量 $> 30 \text{ g} \cdot \text{kg}^{-1}$ 、 $> 40 \text{ g} \cdot \text{kg}^{-1}$ 时处于较高水平。土壤活性磷、中等活性磷含量分布在 CEC 值 $< 6.2 \text{ cmol} \cdot \text{kg}^{-1}$ 、 $6.2 \sim 10.5 \text{ cmol} \cdot \text{kg}^{-1}$ 、 $10.5 \sim 15.4 \text{ cmol} \cdot \text{kg}^{-1}$ 及 $15.4 \sim 20.0 \text{ cmol} \cdot \text{kg}^{-1}$ 范围内的样点比例分别为 24.7%、50.6%、20.2%、3.4%。活性磷和中等活性磷均在 CEC 值高于 $15.4 \text{ cmol} \cdot \text{kg}^{-1}$ 时含量较高 (图 8B)。土壤活性磷、中等活性磷含量在土壤 TN $< 0.5 \text{ g} \cdot \text{kg}^{-1}$ 、 $0.50 \sim 0.75 \text{ g} \cdot \text{kg}^{-1}$ 、 $0.75 \sim 1.00 \text{ g} \cdot \text{kg}^{-1}$ 、 $1.0 \sim 1.5 \text{ g} \cdot \text{kg}^{-1}$ 、 $1.5 \sim 2.0 \text{ g} \cdot \text{kg}^{-1}$ 、 $> 2.0 \text{ g} \cdot \text{kg}^{-1}$ 各含量段的样点分布频率分别为: 19.1%、3.4%、12.4%、37.1%、16.9%、11.2%。土壤 TN 含量高于 1.5 、 $2.0 \text{ g} \cdot \text{kg}^{-1}$ 时土壤活性磷、中等活性磷含量处于较高水平 (图 8C)。图 8D 中, 土壤活性磷、中等活性磷含量分布于 AN $60 \sim 90 \text{ mg} \cdot \text{kg}^{-1}$ 、 $90 \sim 120 \text{ mg} \cdot \text{kg}^{-1}$ 、 $120 \sim 150 \text{ mg} \cdot \text{kg}^{-1}$ 、 $> 150 \text{ mg} \cdot \text{kg}^{-1}$ 含量段的样点比例分别为 12.4%、32.6%、28.1%、27.0%。土壤 AN 含量分别为 120 、 $150 \text{ mg} \cdot \text{kg}^{-1}$ 时土壤活性磷、中等活性磷含量分别处于较高水平。土壤活性磷、中等活性磷含量在土壤 AK $30 \sim 50 \text{ mg} \cdot \text{kg}^{-1}$ 、 $50 \sim 100 \text{ mg} \cdot \text{kg}^{-1}$ 、 $100 \sim 150 \text{ mg} \cdot \text{kg}^{-1}$ 、 $150 \sim 200 \text{ mg} \cdot \text{kg}^{-1}$ 、 $> 200 \text{ mg} \cdot \text{kg}^{-1}$ 含量段的分布频率分别为 6.7%、15.7%、10.1%、18.0% 和 49.4%。其中, 土壤活性磷含量在 AK 含量 $> 150 \text{ mg} \cdot \text{kg}^{-1}$ 时处于较高水平, 中等活性磷含量在 AK 含量 $> 100 \text{ mg} \cdot \text{kg}^{-1}$ 时较高 (图 8E)。

3 讨论

土壤磷库中, 磷以无机磷和有机磷形态存在, 无机磷占总磷库 35%~70%^[31]。针对自然生态系统如林地^[32]、湿地^[33]、草地^[34] 的研究表明, 土壤有机磷在总磷库的占比通常高于无机磷。本研究中, 赤红壤常年菜地呈现出与自然生态系统不同的磷库组成特点: 无机磷在磷库占比远高于有机磷, 无机磷是菜地土壤磷库主导形态。这与针

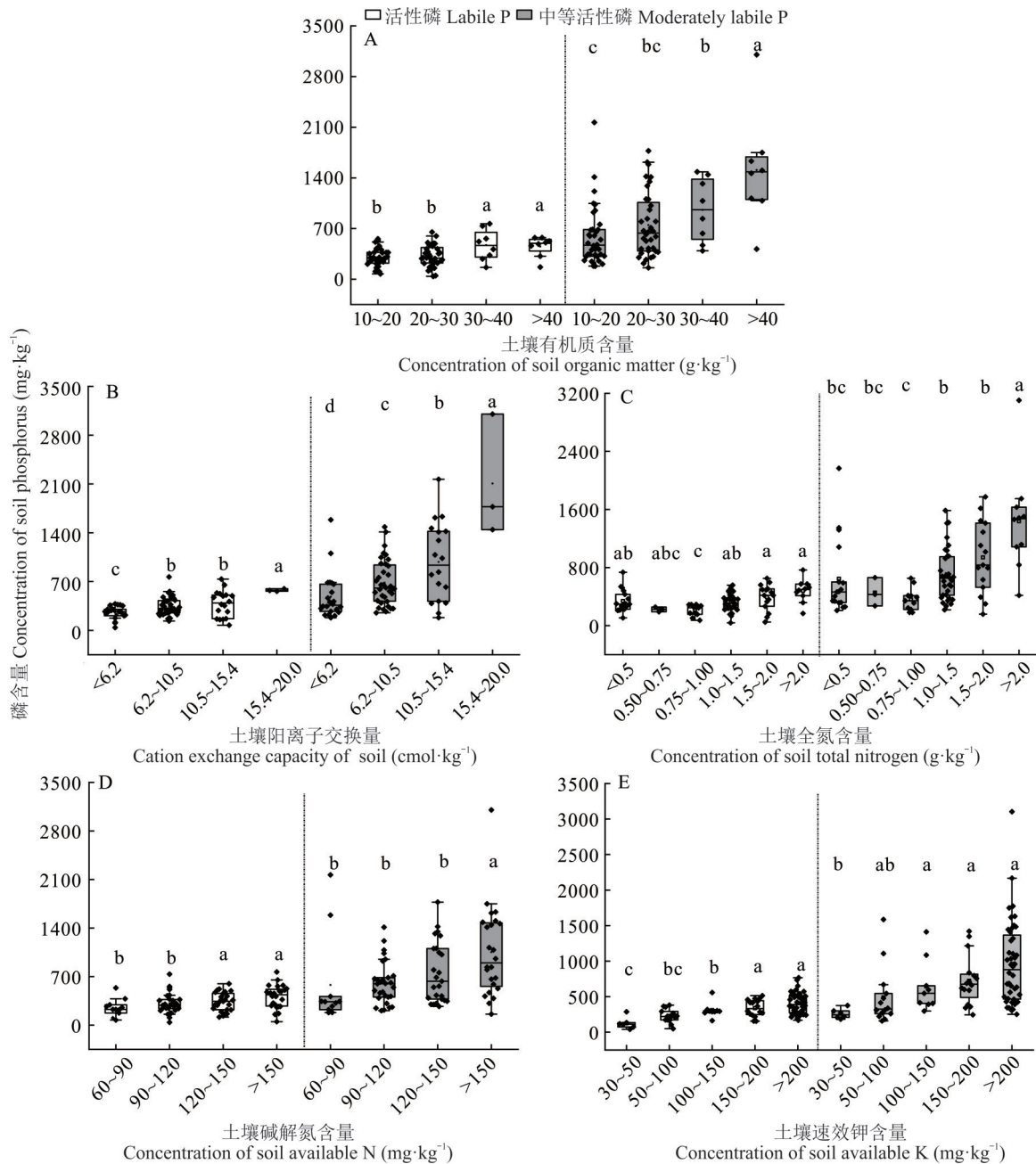


图8 土壤有机质、阳离子交换量、全氮、碱解氮、速效钾分级条件下土壤活性磷、中等活性磷含量分布

Fig. 8 Distribution of labile P, moderately labile P concentration under different grades of soil organic matter, cation exchange capacity, total nitrogen, available nitrogen and available potassium in soil

不同小写字母代表指标梯度含量间差异显著。Different lowercase letters mean the significant difference among the gradient concentrations of soil parameters.

对稻田^[35]、水旱轮作^[36]、旱地^[37]等农田系统的研究结果相似。Cross等^[11]研究表明,在高度风化的土壤中,磷多以非活性、闭蓄态或稳定有机态形式存在。本研究中,供试土壤赤红壤属于高风化土壤类型,土壤磷库中磷主要以无机磷形态赋存,与赤红壤特性及人为活动影响密切相关。赤红壤富含铁铝氧化物,磷肥施入土壤后大部分被固定,转化为Fe-P或Al-P,从而使磷主要以无机磷形式赋存于土壤中^[21]。本研究中,土壤无机磷累积量高是赤红壤常年菜地磷库的另一个特点,体现了广东省耕地地力“富磷”这一典型特征^[38]。Zhang等^[39]、Wang等^[40]、Zhang等^[41]针对集约化菜地的研究也有类似发现,土壤无机磷累积量最高分别达2321、1399、1354.5 mg·kg⁻¹。耕作、施肥管理等人为活动是导致赤红壤常年菜地土壤无机磷累积的直接因素。据广东省耕地肥料用量监测结果,全省

常年菜地化肥投入量最高,年均达 $1639.5 \text{ kg}\cdot\text{hm}^{-2}$,比全省农田平均总养分投入量高65%,且本研究中赤红壤菜地所在的珠三角地区耕地肥料总养分投入量高于全省平均水平^[38]。McDowell等^[42]、Yan等^[43]、Chen等^[44]的研究均表明,集约化种植系统中过量磷的投入主要提高了无机磷储量,造成土壤有机磷在磷库占比较低。刘建玲等^[45]针对长期定位试验的研究显示,长期施肥(磷肥、有机肥)土壤各形态磷库均有不同程度的积累,土壤磷素的积累以无机磷为主。

土壤磷库组成是评价土壤供磷能力的重要指标,土壤磷有效性取决于不同类型活性磷组分的含量及其在磷库占比^[46]。一般认为,活性磷和中等活性磷是土壤有效磷的库源^[47]。活性磷库中, $\text{H}_2\text{O}\text{-Pi}$ 主要存在于土壤溶液中, $\text{NaHCO}_3\text{-P}$ 主要是吸附在土壤颗粒表面的有机磷和无机磷,易被作物直接吸收或易于被微生物降解为可利用态^[29]。本研究中,赤红壤常年菜地活性磷在磷库占比达1/4,且其含量几乎均超过 $40 \text{ mg}\cdot\text{kg}^{-1}$ 这一评价土壤有效磷含量极丰富的标准^[25]。中等活性磷是潜在的有效磷源,磷库中 $\text{NaOH}\text{-P}$ 主要为吸附在土壤铁、铝氧化物表面的磷,稀 HCl 提取的磷为 $\text{Ca}\text{-P}$ ^[26,30]。本研究的供试土壤赤红壤,富含铁铝氧化物,与之密切相关的 $\text{NaOH}\text{-P}(\text{Pi}+\text{Po})$ 平均占总磷库比例达37%,这与龚梦瑶等^[48]针对红壤的研究结果相近。同时, $\text{NaOH}\text{-Pi}$ 、 $\text{NaOH}\text{-Po}$ 分别是赤红壤常年菜地土壤无机磷和有机磷的主要赋存形态,与棕壤^[49]、白浆土^[50]、红壤^[51]、灰钙土^[52]等的相关研究结论一致。赤红壤中钙含量较铁、铝含量低, $\text{HCl}\text{-P}$ 在磷库含量虽低于 $\text{NaOH}\text{-P}$,但其在总磷库、中等活性磷库的平均比例分别达16.32%和35.9%,因其具有持续、缓慢供应特征,是生物磷素重要来源之一^[53]。本研究赤红壤常年菜地中等活性磷含量是相应活性磷含量的1.01~5.54倍,且其在总磷库占主导地位(平均占比达57.1%),与Liao等^[54]的研究结果相似。此外,几乎所有样点土壤活性磷和中等活性磷之和在总磷库占比超过50%。研究结果表明,从土壤有效态磷容量角度,赤红壤常年菜地土壤磷库磷有效性高,这可能与常年菜地长期高量施磷、频繁施肥等管理模式有关^[55]。针对包括珠三角地区在内的广东省蔬菜施肥情况调查结果显示,蔬菜所施化肥中以高浓度、水溶性三元复合肥($\text{N}:\text{P}_2\text{O}_5:\text{K}_2\text{O}=15:15:15$)为主,且蔬菜磷肥用量($456.7 \text{ kg P}_2\text{O}_5\cdot\text{hm}^{-2}$)和磷养分投入比例($\text{N}:\text{P}_2\text{O}_5:\text{K}_2\text{O}$ 为1.00:1.03:0.99)均偏高^[56]。研究表明,施肥是影响活性磷($\text{H}_2\text{O}\text{-P}$ 和 $\text{NaHCO}_3\text{-P}$)含量的重要因素^[46,51],磷肥施入土壤,磷会优先并主要累积于活性磷库^[13]。长期定位试验结果也显示,持续施用磷肥或磷肥配施有机肥增加土壤易溶性磷含量,进而增强土壤磷作物有效性^[57]。与无机磷相比,有机磷在土壤中移动性较大,不易被固定^[58]。通常,有机磷在土壤总磷库中占比约为30%~65%,富含有机质的土壤中有有机磷最高可达90%^[31],是植物和微生物重要的潜在磷源^[59]。本研究中,赤红壤常年菜地有机磷在总磷库的平均占比不足10%,与红壤(5.2%)、潮土(8.7%)、黄绵土(9.3%)有机磷占比相近,高于荒漠土有机磷比例(3.3%),低于黑土有机磷占比(36.9%)^[60],但本研究中菜地有机磷主要以活性和中等活性形态存在,其中活性有机磷($\text{NaHCO}_3\text{-Po}$)、中等活性有机磷($\text{NaOH}\text{-Po}$)含量最高分别达 $81.3 \text{ mg}\cdot\text{kg}^{-1}$ 、 $300 \text{ mg}\cdot\text{kg}^{-1}$ 。研究表明,这两种活性的有机磷在土壤中矿化时间相对较短,其中,活性有机磷矿化时间约为3 d,中等活性有机磷矿化时间在4~13周^[61],赤红壤常年菜地土壤有机磷可作为重要的潜在磷源。

土壤磷库组成和生物有效性与土壤物理化学性质等密切相关^[6]。研究表明,土壤pH值通过调节铁铝氧化物活性^[62]、微生物活性^[63]以及 OH^- 与磷酸根相互作用^[64]等途径对土壤无机磷、有机磷储量及转化产生影响。本研究中,研究区89个常年菜地土壤样点中,土壤pH值与磷库及磷赋存形态之间并无显著相关性,可能与研究区近年来种植结构调整及其他人为活动等导致土壤pH值升高及pH值分布范围较小(约70%样品pH值在5.5~7.5之间)等有关^[65],具体原因有待进一步深入探讨。自然生态系统中碳、氮、磷循环过程的相互作用已被广泛证实^[66-67],有机碳积累有助于提高土壤有机磷含量^[51]、增加磷活性^[46,63],外源氮促进土壤有机磷矿化^[67]、加速磷转化速率^[68]。本研究中,常年菜地土壤磷库及各活性磷含量均与土壤有机质含量、氮含量(全氮、碱解氮)呈显著正相关,且存在浓度效应,这与高有机碳、高氮水平下有助于促进土壤磷库积累的研究结果相似^[69-70]。阳离子交换量是影响土壤磷环境行为的重要因子,离子交换能力高的土壤其对磷的吸附能力相对较高^[71],有助于土壤磷库累积。本研究中,菜地土壤CEC值高于 $15.4 \text{ cmol}\cdot\text{kg}^{-1}$ 时土壤活性磷、中等活性磷含量均处于较高水平,这可能与赤红壤在较高的CEC水平下铁氧化物随还原和溶解过程提高了磷库有效性有关^[72]。研究表明,土壤中钾可通过

多种途径对磷库产生影响:钾离子可增强土壤中有机磷的吸附^[73],也可通过阳离子键桥或共沉淀等途径与磷结合增加土壤磷固存能力^[74]。此外,Han等^[75]研究发现,土壤交换性钾与交换性铝显著负相关,一定程度上土壤钾含量增加有助于提高磷生物有效性。本研究中土壤速效钾含量与活性磷及中等活性磷含量之间的正相关性可能与上述因素有关。

4 结论

针对广东赤红壤区常年菜地这一典型种植系统的研究显示,赤红壤常年菜地土壤普遍呈“富磷”特征,且富含有效态磷。Hedley磷库分级法从磷形态角度明确无机磷是赤红壤常年菜地磷主要赋存形态;从磷生物有效性角度探明中等活性磷在磷库占主导地位,其次为活性磷。不同提取态磷中,NaOH-P分别在无机磷和有机磷库中占主导地位。有机磷库以活性磷和中等活性磷占比较高为主要特征。蔬菜种植过程中施肥、耕作管理等人为活动及赤红壤特性共同塑造土壤磷库现状,其中,土壤有机质、全氮、碱解氮、速效钾等养分指标及土壤阳离子交换性能等是影响磷活性的主要土壤因子。

通常,针对土壤磷供应能力的评价既要考虑土壤有效态磷含量这一静态因素,也要考虑磷从土壤溶液向植物根表迁移这一动态因素,针对赤红壤菜地土壤磷供应能力的全面评价尚需进一步深入探讨。本地区蔬菜种植过程中采取有针对性的养分精准管理技术,充分活化利用土壤残余磷,有助于从源头降低菜地磷素面源污染风险。

本研究针对广东赤红壤区常年菜地土壤磷库特征的识别,为今后该地区土壤磷养分时空变化对比分析等提供了基础数据。

致谢:感谢广东省气候中心王兵高级工程师协助制作土壤采样点分布图。

参考文献 References:

- [1] Cordell D, Drangert J O, Whit S. The story of phosphorus: Global food security and food for thought. *Global Environmental Change*, 2009, 19: 292–305.
- [2] Zhang W, Chen X J, Ma L, *et al.* Re-prediction of phosphate fertilizer demand in China based on agriculture green development. *Acta Pedologica Sinica*, 2023, 60(5): 1389–1397.
张伟, 陈轩敬, 马林, 等. 再论中国磷肥需求预测—基于农业绿色发展视角. *土壤学报*, 2023, 60(5): 1389–1397.
- [3] Zou T, Zhang X, Davidson E A. Global trends of cropland phosphorus use and sustainability challenges. *Nature*, 2022, 611: 81–87.
- [4] Zeng Z B, Zeng S J, Tang J D, *et al.* Space-temporal variation of farmland soil AP in Guangdong province and their causing factors. *Ecology and Environmental Sciences*, 2014, 23(3): 444–451.
曾招兵, 曾思坚, 汤建东, 等. 广东省耕地土壤有效磷时空变化特征及影响因素分析. *生态环境学报*, 2014, 23(3): 444–451.
- [5] Tian J, Boitt G, Black A, *et al.* Accumulation and distribution of phosphorus in the soil profile under fertilized grazed pasture. *Agriculture, Ecosystems and Environment*, 2017, 239: 228–235.
- [6] Su N, Xie G, Mao Z, *et al.* The effectiveness of eight-years phosphorus reducing inputs on double cropping paddy: Insights into productivity and soil-plant phosphorus tradeoff. *Science of the Total Environment*, 2023, 866: 161429.
- [7] Guangdong Rural Statistical Yearbook Editorial Board. 2022 Guangdong rural statistical yearbook. Beijing: China Statistics Press, 2022.
《广东农村统计年鉴》编辑委员会. 2022广东农村统计年鉴. 北京: 中国统计出版社, 2022.
- [8] Olsen S R, Cole C V, Watanabe F S, *et al.* Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *Circular (United States. Department of Agriculture)*, 1954: 939.
- [9] Wyngaard N, Cabrera M L, Jarosch K A, *et al.* Phosphorus in the coarse soil fraction is related to soil organic phosphorus mineralization measured by isotopic dilution. *Soil Biology & Biochemistry*, 2016, 96: 107–118.

- [10] Hedley M J, Stewart J W B, Chauhan B S. Changes inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. *Soil Science Society of America Journal*, 1982, 46: 970–976.
- [11] Cross A F, Schlesinger W H. A literature review and evaluation of the Hedley fractionation: Applications to the biogeochemical cycle of soil phosphorus in natural ecosystems. *Geoderma*, 1995, 64: 197–214.
- [12] Negassa W, Leinweber P. How does the Hedley sequential phosphorus fractionation reflect impacts of land use and management on soil phosphorus: A review. *Journal of Plant Nutrition & Soil Science*, 2010, 172: 305–325.
- [13] Biassoni M M, Vivas H, Gutiérrez-Boem F H, *et al.* Changes in soil phosphorus (P) fractions and P bioavailability after 10 years of continuous P fertilization. *Soil and Tillage Research*, 2023, 232: 105777.
- [14] Maranguit D, Guillaume T, Kuzyakov Y. Land-use change affects phosphorus fractions in highly weathered tropical soils. *Catena*, 2017, 149: 385–393.
- [15] Damian J M, Firmano R F, Cherubin M R, *et al.* Changes in soil phosphorus pool induced by pastureland intensification and diversification in Brazil. *Science of the Total Environment*, 2020, 703: 135463.
- [16] Meason Dean F, Idol Travis W, Friday J B, *et al.* Effects of fertilisation on phosphorus pools in the volcanic soil of a managed tropical forest. *Forest Ecology and Management*, 2009, 258: 2199–2206.
- [17] Fan T, Luo M, Tan J, *et al.* Incorporating biotic phosphorus-acquisition strategies into soil phosphorus transformation under long-term salinization in a tidal wetland. *Catena*, 2023, 231: 107274.
- [18] Li J, Wu B, Zhang D, *et al.* Elevational variation in soil phosphorus pools and controlling factors in alpine areas of Southwest China. *Geoderma*, 2023, 431: 116361.
- [19] Anthonio C K, Jing H, Jin C, *et al.* Impact of long-term fertilization on phosphorus fractions and manganese oxide with their interactions in paddy soil aggregates. *Journal of Environmental Management*, 2023, 333: 117440.
- [20] Zheng L, Zhao Q, Lin G, *et al.* Nitrogen addition impacts on soil phosphorus transformations depending upon its influences on soil organic carbon and microbial biomass in temperate larch forests across northern China. *Catena*, 2023, 230: 107252.
- [21] Guangdong Provincial Soil Survey Office. *Guangdong soil*. Beijing: Science Press, 1993.
广东省土壤普查办公室. *广东土壤*. 北京: 科学出版社, 1993.
- [22] Kochian L V. Rooting for more phosphorus. *Nature*, 2012, 488: 466–467.
- [23] Ning J, Yao J, Wang R, *et al.* Phosphorus status and adsorption characteristics of perennial vegetable-cultivated soils in South China. *PLoS One*, 2022, 17: e0264189.
- [24] Ning J F, Li T, Zeng R K, *et al.* Soil fertility in perennial vegetable fields in the latosolic red soil zone of the Pearl River Delta. *Acta Prataculturae Sinica*, 2024, 33(5): 25–40.
宁建凤, 李彤, 曾瑞锟, 等. 珠三角赤红壤常年菜地土壤肥力质量评价. *草业学报*, 2024, 33(5): 25–40.
- [25] National Soil Census Office. *China soil census technology*. Beijing: Agricultural Publishing House, 1992.
全国土壤普查办公室. *中国土壤普查技术*. 北京: 农业出版社, 1992.
- [26] Tiessen H, Moir J O. Characterization of available P by sequential extraction//Carter M R. (Ed.), *Soil sampling and methods of analysis*. Lewis Publishers, Boca Raton, Canadian Society of Soil Science, 1993: 75–86.
- [27] Murphy J, Riley J P. A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta*, 1962, 27: 31–36.
- [28] Lu R K. *Methods of soil agrochemical analysis*. Beijing: China Agricultural Science and Technology Press, 2000.
鲁如坤. *土壤农化分析方法*. 北京: 中国农业科技出版社, 2000.
- [29] Bowman R A, Cole C V. An exploratory method for fractionation of organic phosphorus from grassland soils. *Soil Science*, 1978, 125: 95–101.
- [30] Ahmed W, Qaswar M, Huang J, *et al.* Tillage practices improve rice yield and soil phosphorus fractions in two typical paddy soils. *Journal of Soils and Sediments*, 2020, 20: 850–861.
- [31] Harrison A F. *Soil organic phosphorus—A review of world literature*. Oxon C. A. B. International United Kingdom, Wallingford, 1987.
- [32] Chen H, Chen M, Li D, *et al.* Responses of soil phosphorus availability to nitrogen addition in a legume and a non-legume plantation. *Geoderma*, 2018, 322: 12–18.
- [33] Li Y H. Accumulation and paleo environmental implications of phosphorus in mid-high latitude peatlands, Northeast China.

- Beijing: University of Chinese Academy of Sciences, 2022.
- 李蕴慧. 中高纬湿地磷的累积及环境指示意义. 北京: 中国科学院大学, 2022.
- [34] Gao X L, Li X G, Zhao L, *et al.* Regulation of soil phosphorus cycling in grasslands by shrubs. *Soil Biology and Biochemistry*, 2019, 133: 1–11.
- [35] Lin C, Wang F, He C M, *et al.* Effects of long term fertilization on phosphorus pools and forms in yellow paddy fields of southern China. *Journal of Plant Nutrition and Fertilizers*, 2014, 20(3): 541–549.
- 林诚, 王飞, 何春梅, 等. 长期不同施肥对南方黄泥田磷库及其形态的影响. *植物营养与肥料学报*, 2014, 20(3): 541–549.
- [36] Chen F, Wang X S, Gan G Y, *et al.* Effects of long-term application of phosphorus fertilizer on soil phosphorus fractions and microbial diversity in rice-rapeseed rotation. *Journal of Huazhong Agricultural University*, 2021, 40(1): 168–178.
- 陈凤, 王晓双, 甘国渝, 等. 长期施用磷肥对稻—油轮作土壤磷组分及微生物多样性的影响. *华中农业大学学报*, 2021, 40(1): 168–178.
- [37] Sun R P. Changes in phosphorus fractions in the plough layer of loess soil under long-term contrasting soil management regimes. Yangling: Northwest A & F University, 2015.
- 孙锐璞. 不同管理壤土耕层土壤磷组分的变化. 杨凌: 西北农林科技大学, 2015.
- [38] Department of Agriculture and Rural Affairs of Guangdong Provincial. Brief report on cultivated land quality monitoring in Guangdong Province in 2019. http://dara.gd.gov.cn/zwgk2278/bmdt/content/post_3077919.html.
- 广东省农业农村厅. 广东省2019年度耕地质量监测简报. http://dara.gd.gov.cn/zwgk2278/bmdt/content/post_3077919.html.
- [39] Zhang Y J, Gao W, Luan H A, *et al.* Effects of a decade of organic fertilizer substitution on vegetable yield and soil phosphorus pools, phosphatase activities, and the microbial community in a greenhouse vegetable production system. *Journal of Integrative Agriculture*, 2022, 21: 2119–2133.
- [40] Wang Y, Zhang H, Tang J, *et al.* Accelerated phosphorus accumulation and acidification of soils under plastic greenhouse condition in four representative organic vegetable cultivation sites. *Scientia Horticulturae*, 2015, 195: 67–73.
- [41] Zhang G S, Ni Z W. Soil phosphorus fractions in aggregate size classes in southwestern China. *Soil Use and Management*, 2018, 34: 266–275.
- [42] McDowell R W, Condon L M. Phosphorus and the Winchmore trials: Review and lessons learnt. *New Zealand Journal of Agricultural Research*, 2012, 55: 119–132.
- [43] Yan Z, Chen S, Li J, *et al.* Manure and nitrogen application enhances soil phosphorus mobility in calcareous soil in greenhouses. *Journal of Environmental Management*, 2016, 181: 26–35.
- [44] Chen S, Yan Z, Zhang S, *et al.* Nitrogen application favors soil organic phosphorus accumulation in calcareous vegetable fields. *Biology and Fertility of Soils*, 2019, 55: 481–496.
- [45] Liu J L, Zhang F S. Dynamics of soil P pool in a long-term fertilizing experiment of wheat-maize rotation I. Crop yield effect of fertilizer P and dynamics of soil total P and inorganic P. *Chinese Journal of Applied Ecology*, 2000, 11(3): 360–364.
- 刘建玲, 张福锁. 小麦—玉米轮作长期肥料定位试验中土壤磷库的变化I. 磷肥产量效应及土壤总磷库、无机磷库的变化. *应用生态学报*, 2000, 11(3): 360–364.
- [46] Wang Z R, Li F R, Liu L L, *et al.* Changes in soil phosphorus fractions under different land uses in desert grasslands in Northwestern China. *European Journal of Soil Science*, 2022, 73: e13255.
- [47] Weand M P, Arthur M A, Lovett G M, *et al.* The phosphorus status of northern hardwoods differs by species but is unaffected by nitrogen fertilization. *Biogeochemistry*, 2010, 97(2): 159–181.
- [48] Gong M Y, Li Q Y, Chen A L, *et al.* Long-term abandonment of reddish paddy fields decreases soil phosphorus pool. *Journal of Plant Nutrition and Fertilizers*, 2022, 28(8): 1398–1408.
- 龚梦瑶, 李巧云, 陈安磊, 等. 长期弃耕降低红壤稻田土壤磷库. *植物营养与肥料学报*, 2022, 28(8): 1398–1408.
- [49] Zhu J Y, Han X R, Yang J F, *et al.* Effect of 30 years' crop rotated fertilization on the temporal variation of phosphorus pool in brown earth. *Chinese Journal of Soil Science*, 2011, 42(4): 891–895.
- 朱佳颖, 韩晓日, 杨劲峰, 等. 30年轮作施肥对棕壤磷库时间变异特征的影响. *土壤通报*, 2011, 42(4): 891–895.
- [50] Li H B, Li D P, Wu Z J, *et al.* Albic soil phosphorus fractions after different years of cultivation. *Chinese Journal of Soil Science*, 2014, 45(1): 135–140.

- 李会彬, 李东坡, 武志杰, 等. 不同开垦年限白浆土土壤磷库特征. 土壤通报, 2014, 45(1): 135—140.
- [51] Tian L, Guo Q, Yu G, *et al.* Phosphorus fractions and oxygen isotope composition of inorganic phosphate in typical agricultural soils. *Chemosphere*, 2020, 239: 124622.
- [52] Teng Z Q, Li X D, Han H G, *et al.* Effects of land use patterns on soil phosphorus fractions in the Longzhong part of the Loess Plateau. *Acta Prataculturae Sinica*, 2013, 22(2): 30—37.
滕泽琴, 李旭东, 韩会阁, 等. 土地利用方式对陇中黄土高原土壤磷组分的影响. 草业学报, 2013, 22(2): 30—37.
- [53] Richter D D, Allen H L, Li J W, *et al.* Bioavailability of slowly cycling soil phosphorus: Major restructuring of soil P fractions over four decades in an aggrading forest. *Oecologia*, 2006, 150(2): 259—271.
- [54] Liao D, Zhang C C, Lambers H, *et al.* Changes in soil phosphorus fractions in response to long-term phosphate fertilization under sole cropping and intercropping of maize and faba bean on a calcareous soil. *Plant and Soil*, 2021, 463(1/2): 589—600.
- [55] Li G H, Xu R S, Meng H Y, *et al.* Current situation and countermeasures of fertilizer use in vegetable fields in Nanhai District, Foshan City. *Guangdong Agricultural Sciences*, 2005(6): 52—53.
李广豪, 徐润生, 蒙辉远, 等. 佛山市南海区菜地化肥使用现状及对策. 广东农业科学, 2005(6): 52—53.
- [56] Guan L L, Fu G N, Xu P J, *et al.* Investigation and analysis of fertilization status of vegetable soil in Guangdong Province. *Journal of Southern Agriculture*, 2014, 45(3): 420—424.
官利兰, 伏广农, 徐鹏举, 等. 广东省菜园土壤施肥状况调查与分析. 南方农业学报, 2014, 45(3): 420—424.
- [57] Zhan X Y. Relationship between available phosphorus and phosphorus balance and its mechanism under different long-term fertilizations in black soil. Beijing: Chinese Academy of Agricultural Sciences, 2016.
展晓莹. 长期不同施肥模式黑土有效磷与磷盈亏响应关系差异的机理. 北京: 中国农业科学院, 2016.
- [58] Zhang X Z, Yang X B, Li T X, *et al.* Characteristics of phosphorus uptake and phosphorus fractions in the rhizosphere among different phosphorus efficiency wheat cultivars. *Scientia Agricultura Sinica*, 2012, 45(15): 3083—3092.
张锡洲, 阳显斌, 李廷轩, 等. 不同磷效率小麦对磷的吸收及根际土壤磷组分特征差异. 中国农业科学, 2012, 45(15): 3083—3092.
- [59] Li B Z, Gunina A, Zhran M, *et al.* Fate of low-molecular-weight organic phosphorus compounds in the P-rich and P-poor paddy soils. *Journal of Integrative Agriculture*, 2021, 20(9): 2526—2534.
- [60] Lu R K, Shi Z Y, Qian C L. Study on soil accumulated phosphorus-morphological characteristics and effectiveness of accumulated phosphorus in several typical soils. *Soils*, 1997(2): 57—60, 75.
鲁如坤, 时正元, 钱承梁. 土壤积累态磷研究—几种典型土壤中积累态磷的形态特征及其有效性. 土壤, 1997(2): 57—60, 75.
- [61] Darch T, Blackwell M S A, Hawkins J M B, *et al.* A meta-analysis of organic and inorganic phosphorus in organic fertilizers, soils, and water: implications for water quality. *Critical Reviews in Environmental Science and Technology*, 2014, 44: 2172—2202.
- [62] Carreira J A, García-Ruiz R, Liétor J, *et al.* Changes in soil phosphatase activity and P transformation rates induced by application of N- and S-containing acid mist to a forest canopy. *Soil Biology and Biochemistry*, 2000, 32(13): 1857—1865.
- [63] Qin L, Jian M, Freeman C, *et al.* Agricultural land use regulates the fate of soil phosphorus fractions following the reclamation of wetlands. *Science of the Total Environment*, 2023, 863: 160891.
- [64] Sui L, Tang C, Cheng K, *et al.* Biochar addition regulates soil phosphorus fractions and improves release of available phosphorus under freezing-thawing cycles. *Science of the Total Environment*, 2022, 848: 157748.
- [65] Zheng C, Guo Z X, Yuan Y Z, *et al.* Spatial and temporal changes of farmland soil acidification and their influencing factors in different regions of Guangdong Province, China. *Chinese Journal of Applied Ecology*, 2019, 30(2): 593—601.
郑超, 郭治兴, 袁宇志, 等. 广东省不同区域农田土壤酸化时空变化及其影响因素. 应用生态学报, 2019, 30(2): 593—601.
- [66] Schleuss P M, Widdig M, Heintz-Buschar A, *et al.* Stoichiometric controls of soil carbon and nitrogen cycling after long-term nitrogen and phosphorus addition in a mesic grassland in South Africa. *Soil Biology and Biochemistry*, 2019, 135: 294—303.
- [67] Wang Z, Zhao M, Yan Z, *et al.* Global patterns and predictors of soil microbial biomass carbon, nitrogen, and phosphorus in terrestrial ecosystems. *Catena*, 2022, 211: 106037.
- [68] Marklein A R, Houlton B Z. Nitrogen inputs accelerate phosphorus cycling rates across a wide variety of terrestrial ecosystems.

New Phytologist, 2012, 193: 696–704.

- [69] Lu P, Li W H, Niu J C, *et al.* Phosphorus availability and transformation of inorganic phosphorus forms under different organic carbon levels in a tier soil. *Scientia Agricultura Sinica*, 2022, 55(1): 111–122.
路鹏, 李文海, 牛金璨, 等. 不同有机碳水平下壤土磷的有效性及无机磷形态转化. *中国农业科学*, 2022, 55(1): 111–122.
- [70] Liu Y, Bing H J, Wu Y H, *et al.* Nitrogen addition promotes soil phosphorus availability in the subalpine forest of eastern Tibetan Plateau. *Journal of Soil and Sediments*, 2022, 22: 1–11.
- [71] Wang H, Tang S, Han S, *et al.* Effects of long-term substitution of chemical fertilizer with Chinese milk vetch on soil phosphorus availability and leaching risk in the double rice systems of Eastern China. *Field Crops Research*, 2023, 302: 109047.
- [72] Cui H J, Wang M K, Fu M L, *et al.* Enhancing phosphorus availability in phosphorus-fertilized zones by reducing phosphate adsorbed on ferrihydrite using rice straw-derived biochar. *Journal of Soils and Sediments*, 2011, 11: 1135.
- [73] Zhao D, Qiu S K, Li M M, *et al.* Modified biochar improves the storage capacity and adsorption affinity of organic phosphorus in soil. *Environmental Research*, 2022, 205: 112455.
- [74] Xue P, Hou R, Fu Q, *et al.* Potentially migrating and residual components of biochar: Effects on phosphorus adsorption performance and storage capacity of black soil. *Chemosphere*, 2023, 336: 139250.
- [75] Han T, Li D, Liu K, *et al.* Soil potassium regulation by initial K level and acidification degree when subjected to liming: A meta-analysis and long-term field experiment. *Catena*, 2023, 232: 107408.