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渭北旱地苹果园生草覆盖下不同肥料配施对土壤养分和酶活性的影响

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摘 要 试验采取裂区设计,主处理分别为行间生草覆盖和清耕,副处理为4个施肥处理,具体为不施肥(CK)、单施有机肥(M)、氮磷钾配合(NPK)、有机肥与氮磷钾肥配合(MNPK),采用微孔板荧光法研究生草覆盖条件下不同肥料配施对果园土壤酶活性的影响.结果表明:生草刈割覆盖后土壤含水量、有效磷、硝态氮含量和β-1,4-木糖苷酶(βX)、β-1,4-N-乙酰基氨基葡萄糖苷酶(NAG)、β-1,4-葡萄糖苷酶(βG)、纤维二糖水解酶(CBH)活性均显著高于刈割前,土壤全氮、有机碳含量和碱性磷酸酶(AKP)活性在刈割前后差异均不显著.生草覆盖处理的土壤全氮、有机碳含量和土壤βX、NAG、βG、CBH、AKP活性在刈割前后均显著高于清耕处理,但土壤含水量、有效磷、硝态氮含量在刈割前则显著低于清耕处理.生草覆盖条件下,有机肥添加处理(M和MNPK处理)的土壤全氮、有效磷、有机碳含量在刈割前后均显著高于CK和NPK处理,其中MNPK处理的βX、βG、CBH、NAG、AKP等5种酶活性在刈割后均显著高于NPK处理.清耕条件下,MNPK处理的土壤有效磷、有机碳、硝态氮、全氮含量和βG、CBH、AKP活性在刈割前后均显著高于CK和NPK处理.冗余分析结果表明,土壤酶活性与土壤养分因子之间存在显著相关关系,可以利用土壤酶活性来反映土壤肥力状况.综上所述,生草覆盖条件下,有机无机配施显著提高了土壤养分含量、增强了土壤酶活性,是改善当前果园土壤质量下降的重要措施,对当地苹果产业的可持续发展具有重要意义.

关键词 土壤酶活性; 微孔板荧光法; 冗余分析; 土壤质量

Effects of grass cover combined with different fertilization regimes on soil nutrients and enzyme activities in apple orchard in Weibei dryland, China.

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Abstract: The split-plot design was adopted in this experiment, with main treatments of grass cover and control and sub-treatments included four fertilization regimes: no fertilization, CK; manure, M; N, P and K fertilizer, NPK; and NPK fertilizer combined with manure, MNPK. Microplate fluorimetry was used to study the effects of grass cover combined with different fertilization regimes on the enzyme activities in apple orchard. The results showed that after mowing the grass (the residues were left on the soil surface as mulch), the soil water content, available P, nitrite nitrogen and the activities of βX, NAG, βG, CBH were increased compared to the control, with no significant differences for total nitrogen, soil organic carbon, and AKP activity. For grass cover treatment, the

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total nitrogen, soil organic carbon, and the activities of βX, NAG, βG, CBH, AKP were both improved before and after mowing the grass. However, the soil water content, available phosphorus, and nitrate nitrogen of grass cover treatment were lower than that of the control before mowing the grass. Under grass cover condition, the total nitrogen, available P, and soil organic carbon of M and MNPK were higher than that of CK and NPK in both before and after mowing the grass periods, with the activities of βX, NAG, βG, CBH, AKP of MNPK higher than that of NPK. Under the control condition, the available P, soil organic carbon (SOC), nitrite nitrogen, total nitrogen and the activities of βG, CBH, AKP of MNPK higher than that of CK and NPK before and after mowing the grass. Redundancy analysis showed that the activities of soil enzymes were significantly correlated with the soil nutrients, and could reflect the soil fertility. Thus, grass cover combined with MNPK significantly increased the soil nutrient contents and soil enzyme activities, and was an important practice to prevent the decrease of soil fertility and benefit the sustainability of local apple industry.

Key words: soil enzyme activity; microplate fluorimetric assay; redundancy analysis; soil quality.

陕西省既是我国苹果第一生产大省,又是世界上公认的最大集中连片优质苹果产区,在我国乃至世界苹果产业发展中具有十分重要的地位[1-3].近年以渭北旱塬为代表的陕西苹果产业得到迅猛发展,但当地果农对大规模商品化栽培方面经验不足,果园管理粗放,加之缺乏对合理施肥的深入了解,长期以来果园的施肥以化肥为主,忽视有机肥的施用,从而导致土壤板结、肥力下降、养分不平衡等问题[4-6],造成果园产量低且不稳定[7].生草覆盖和有机无机配施是苹果生产中提高土壤肥力和果树产量的重要措施.生草覆盖作为国际上推行的一项现代化、标准化的果园管理措施,具有保持土壤水分、减少土壤侵蚀、改善土壤理化性质、提高果实产量和品质[8-14]的特点;有机肥的施用增加了土壤有机质含量,促进了土壤微生物活动,提高了土壤酶活性,从而提高了土壤养分有效性,大大增强了土壤肥力[15-16].李涛涛等[17]在渭北旱塬果园研究中发现,生草覆盖并配合施用有机无机肥是旱地果园提高树体生长发育、获得高产的最佳模式.土壤酶参与土壤生物化学过程,既是土壤有机物转化的执行者,又是植物营养元素的活化库[18],酶活性在土壤中的表现在一定程度上反映了土壤所处的状态,且对环境等外界因素引起的变化较为敏感,是生态系统变化的预警和敏感指标[19-21].生草覆盖在渭北旱塬苹果生产系统中的应用研究也有近几十年的历史,但前人研究主要集中在生草覆盖对土壤水分、理化性质、土壤侵蚀和苹果产量这几方面[22-23],对果园土壤质量的变化关注很少,在果园生草覆盖配施肥料条件下从土壤酶活性角度对果园土壤质量进行评价更是鲜有报道.本研究采用高通量微孔板荧光酶活性测定方法[24-25],从土壤胞外酶活性的角度评价生草覆盖条件下不同肥料配施对果园土壤生物学性质的影响,以期为有机肥替代化肥、提高果园土壤质量、促进苹果产业的可持续发展提供理论依据和技术支撑.

1 研究地区与研究方法

1.1 试验地概况

本试验在位于陕西省白水县的西北农林科技大学苹果试验站内进行.试验站地处 35°4′—35°27′ N、109°16′—109°45′ E,年均降水量 570 mm,年际变化较大,冬春干旱少雨,年均气温 11.4 ℃,年极端最高、最低气温分别为 39.4、-16.7 ℃,无霜期 207 d.试验地土壤类型为黄绵土,质地中壤,其基础肥力水平为:有机质 13.02 g·kg^{-1}、全氮 1.03 g·kg^{-1}、硝态氮 22.70 mg·kg^{-1}、铵态氮 2.20 mg·kg^{-1}、有效磷 15.94 mg·kg^{-1}、速效钾 151.28 mg·kg^{-1}、pH 8.30.

1.2 供试材料

供试品种为矮化中间砧‘长富二号’(*Malus pumila* Mil.)富士系列,基砧为 M26,果树为 10 年树龄,2010 年开始结果,株行距为 2 m×4 m,为自由纺锤形树形,行间生草为小冠花,于 2008 年 3 月开始进行行间生草播种,现已持续生草 9 年,播前深翻整地,开沟条播,播种量为 0.75 g·m^{-2},每年 7—9 月每月刈割一次,刈割后地上部覆盖于苹果树行间,果树生长期内对清耕带定期除草,各处理区的生态条件和田间管理措施保持一致.

1.3 试验设计

试验采取裂区设计,两个主处理分别为行间生草覆盖和清耕,副处理为 4 个施肥处理,具体为不施肥(CK)、单施有机肥(M)、氮磷钾配合(NPK)、有机肥与氮磷钾肥配合(MNPK).每个处理重复 3 次,小区面积 200 m^2.施用肥料为尿素(N 46%)、过磷酸

钙(P_2O_5 16%)和硫酸钾(K_2O 50%),有机肥为羊粪,含有机质 35.02 g·kg^{-1}、全氮 5.33 g·kg^{-1}、速效磷(P_2O_5)39 mg·kg^{-1}、速效钾(K_2O) 41 mg·kg^{-1},具体副处理各施肥量见表 1.有机肥和磷肥以基肥形式于秋季一次性施入;氮钾肥分 3 次,即 50%作基肥于秋季施入,30%于开花期和 20%于果实膨大期以追肥方式施入.

1.4　样品采集

于 2016 年 6 月 2 日和 2016 年 10 月 1 日两次采集 0~20 cm 土层土样(去除 5 cm 表土),树冠树行分别采集 6 钻土壤,混合作为一个土样.每个土样分为 3 部分,一部分土样过 2 mm 筛后除去石子和根系残体,放置冰桶带回实验室并放置 4 ℃冰箱保存,用于土壤酶活性的测定;一部分鲜土样用于测定土壤含水量、硝态氮;一部分土样自然风干用于土壤有机碳、全氮、速效磷的测定.

1.5　土壤理化性状和胞外酶活性测定

土壤含水量采用烘干法测定;有效磷(Olsen P)采用 $NaHCO_3$ 钼锑抗比色法测定;土壤硝态氮(NO_3^--N)用 1 mol·L^{-1} 的 KCl 浸提(土水比为 1∶5),滤液用连续性流动分析仪测定;有机碳采用重铬酸钾滴定法测定;全氮采用半微量凯氏法测定.采用改进的 Marx 等[24]的荧光微孔板检测技术测定 β-1,4-木糖苷酶(βX)、β-1,4-N-乙酰基氨基葡萄糖苷酶(NAG)、β-1,4-葡萄糖苷酶(βG)、纤维二糖水解酶(CBH)和碱性磷酸酶(AKP)5 种酶活性,土壤样品 6 次重复,标准和阴性 6 次重复,空白和淬火 3 次重复,该方法是在低底物浓度条件下,通过检测酶裂解释放荧光基团(4-甲基伞形酮酰)所发出的荧光强度进行测定,能直接、快速、灵敏地反映微生物胞外酶活性.荧光底物购自 Sigma-Aldrich 有限公司.

1.6　数据处理

采用 SPSS 20.0 和 Canoco 5.0 软件对数据进行统计分析.采用两因素(two-way ANOVA)和Duncan 法进行方差分析和多重比较($\alpha=0.05$).利用 SigmaPlot 12.5 和 Canoco 5.0 软件作图.

表 1　施肥处理和施肥量

Table 1　Fertilization treatment and application rate of fertilizers (kg·hm^{-2})

处理 Treatment	羊粪 Sheep manure	N	P_2O_5	K_2O
CK	0	0	0	0
NPK	0	192	108	168
MNPK	18000	96	108	168
M	36000	0	0	0

2　结果与分析

2.1　生草覆盖条件下不同肥料配施对土壤基本性质的影响

生草覆盖条件下不同肥料配施影响了土壤养分含量和土壤的保水能力(表 2).生草刈割覆盖后土壤含水量、速效磷、硝态氮的含量显著高于刈割前,分别比刈割前增加了 12.8%、1%、122.2%,但全氮、有机碳的含量差异不显著.生草覆盖处理的土壤全氮、有机碳的含量在刈割前后均显著高于清耕处理.刈割前生草覆盖处理的土壤含水量、速效磷、硝态氮含量显著低于清耕处理,刈割覆盖后则显著高于清耕处理.

生草覆盖条件下,添加有机肥处理(M 和 MNPK 处理)土壤全氮、速效磷、有机碳含量在刈割前后均显著高于 CK 和 NPK 处理,处理间呈 MNPK>M>NPK>CK 的趋势;与 NPK 处理相比,MNPK 处理的硝态氮含量显著增加,刈割前增加了 32.1%,而刈割后增加了 65.1%;CK 处理的土壤含水量在刈割前显著高于 NPK 和 MNPK 处理,而在刈割覆盖后则显著低于 MNPK 处理(15.7%),且与 NPK 处理间无显著差异.

清耕条件下,添加有机肥处理(M 和 MNPK 处理)土壤速效磷、有机碳、硝态氮含量在刈割前后均显著高于 CK 和 NPK 处理,其中 MNPK 处理与 NPK 处理相比,在刈割前分别增加了 101.9%、11.3%、36%,在刈割覆盖后分别增加了 24.2%、9%、55.7%;MNPK 处理的全氮含量刈割前后均显著高于 NPK、M 和 CK 处理;CK 处理的土壤含水量在刈割前显著高于其他施肥处理,而在刈割覆盖后处理间则呈 MNPK>M>NPK>CK 的趋势.

2.2　生草覆盖条件下不同肥料配施对土壤酶活性的影响

生草覆盖条件下不同肥料配施对土壤 C、N、P 循环的酶具有显著影响(图 1).生草刈割覆盖后除磷酸酶外,βX、NAG、βG、CBH 活性均显著高于刈割前,分别比刈割前增加了 26.3%、60.9%、1.8%、86.1%.刈割前后生草处理的 βX、NAG、βG、CBH、AKP 活性均显著高于清耕处理.

βX、βG、CBH 参与土壤中纤维素的降解.生草条件下,MNPK 处理的 βX 活性在刈割前后均显著高于 NPK 和 CK 处理,其中与 NPK 处理相比分别增

表 2 生草覆盖条件下不同肥料配施对土壤基本性质的影响

Table 2 Effects of different fertilization regimes on soil basic properties under grass mulching

时间 Time	耕作措施 Cultivation measure	处理 Treatment	水分 Moisture (%)	全氮 Total N (g·kg⁻1)	速效磷 Olsen P (mg·kg⁻¹)	有机碳 SOC (g·kg⁻¹)	硝态氮 NO_3^--N (mg·kg⁻¹)
BGM	GM	CK	14.0a	0.72c	11.09d	9.79c	5.16c
		M	14.0a	0.98a	19.44b	11.3a	6.93ab
		NPK	12.8b	0.85b	14.94c	10.51b	6.13bc
		MNPK	12.1b	1.08a	23.93a	11.49a	8.10a
	CT	CK	14.9a	0.72c	11.45d	8.72c	6.28b
		M	14.2b	0.83ab	34.58b	10.38a	12.44a
		NPK	14.1b	0.8bc	23.9c	9.48b	9.17b
		MNPK	13.3c	0.93a	48.25a	10.55a	12.47a
	GM		13.2B	0.91A	17.35B	10.77A	6.58B
	CT		14.1A	0.82B	29.55A	9.78B	10.09A
AGM	GM	CK	14.9b	0.76d	15.95c	10.08c	9.49d
		M	16.7a	1.06b	26.21b	12.11a	22.02b
		NPK	16.2ab	0.87c	20.36c	11.21b	17.30c
		MNPK	17.2a	1.11a	46.12a	12.37a	28.57a
	CT	CK	13.1c	0.74c	11.23d	8.46c	8.39d
		M	14.8b	0.89b	21.86b	10.51a	21.03b
		NPK	14.6b	0.84b	17.42c	9.54b	16.15c
		MNPK	16.1a	1.00a	30.35a	10.39a	25.15a
	GM		16.3A	0.95A	27.16A	11.44A	19.35A
	CT		14.61B	0.87B	20.21B	9.73B	17.68B
	BGM		13.7	0.86	23.45	10.28	8.33
	AGM		15.4***	0.91	23.69*	10.58	18.51***

BGM: 生草刈割前 Before the grass mowing; AGM: 生草刈割后 After the grass mowing; GM: 生草覆盖 Grass mulch; CT: 清耕处理 Clean tillage. 同列数据后不同小写字母表示副处理间差异显著, 不同大写字母表示主处理间差异显著($P<0.05$) Different small and capital letters in the same column meant significant difference at 0.05 level among the subsidiary treatments and the main treatments, respectively. * $P<0.05$; *** $P<0.001$.

加了 22.8% (刈割前)和 54.7%(刈割后);MNPK 处理 βG、CBH 活性与 NPK 处理相比在刈割前差异不显著,而在刈割后则显著高于 NPK 处理,与 NPK 处理相比分别增加了 34.5%、58.8%,其中 NPK 处理的 CBH 活性与 CK 处理在刈割前后差异均不显著.清耕条件下,MNPK 处理的 βX 活性与 NPK 处理在刈割前后差异均不显著;添加有机肥处理(M 和 MNPK 处理)土壤 βG、CBH 活性在刈割前后均显著高于 CK 和 NPK 处理,其中 NPK 处理的 CBH 活性与 CK 处理在刈割前后差异均不显著.

NAG 是一种几丁质酶,参与几丁质转化氨基糖的过程,氨基糖[26]占土壤有机氮的 5%~10%,是土壤可矿化氮的主要来源,因此 NAG 活性的高低控制着 N 循环速率[27].生草覆盖下,MNPK 处理的 NAG 活性在刈割前后均显著高于 NPK 处理,分别比 NPK 处理增加了 15.9%和 42%;清耕条件下,NPK 和 CK 处理间 NAG 活性在刈割前后无显著差异,MNPK 处理的 NAG 活性在刈割前显著高于 NPK 处理,与 NPK 处理相比增加了 27.4%,而在刈割后与 NPK 处理相比也有增加的趋势,但差异不显著.

AKP 可催化磷酸脂类或磷酸酐的水解,其活性的高低直接影响着土壤有机磷的分解转化及其生物有效性[28].生草覆盖下,添加有机肥处理(MNPK 和 M 处理)土壤 AKP 活性与 NPK 处理在刈割前差异不显著,而在刈割后则显著高于 NPK 处理,与 NPK 处理相比,分别增加了 31.9%、20.7%,处理间在刈割前后总体呈 MNPK>M>NPK>CK 的趋势;清耕条件下,添加有机肥处理(M 和 MNPK)土壤 AKP 活性在刈割前后均显著高于 CK 和 NPK 处理,其中 MNPK 处理与 NPK 处理相比分别增加了 10.1%(刈割前)和 11.8%(刈割后).

2.3 土壤基本性质与土壤酶活性的相关性

由图 2 可知,刈割前土壤酶活性在第 1 轴、第 2 轴上的解释量分别为 69%和 2%,冗余分析(RDA)前两个排序轴保留了土壤酶活性数据总方差的 71%,即 4 个环境因子累计解释土壤酶活性特征的 71%,且对土壤酶活性与环境因子关系的累计解释量达 98.9%;刈割后土壤酶活性在第 1 轴、第 2 轴上的解释量分别为 80%和 1%,RDA 前两个排序轴保留了土壤酶活性数据总方差的 81%,即 4 个环境因子累计解释土壤酶活性特征的 81%,且对土壤酶活性与环境因子关系的累计解释量达99.7%.由此可

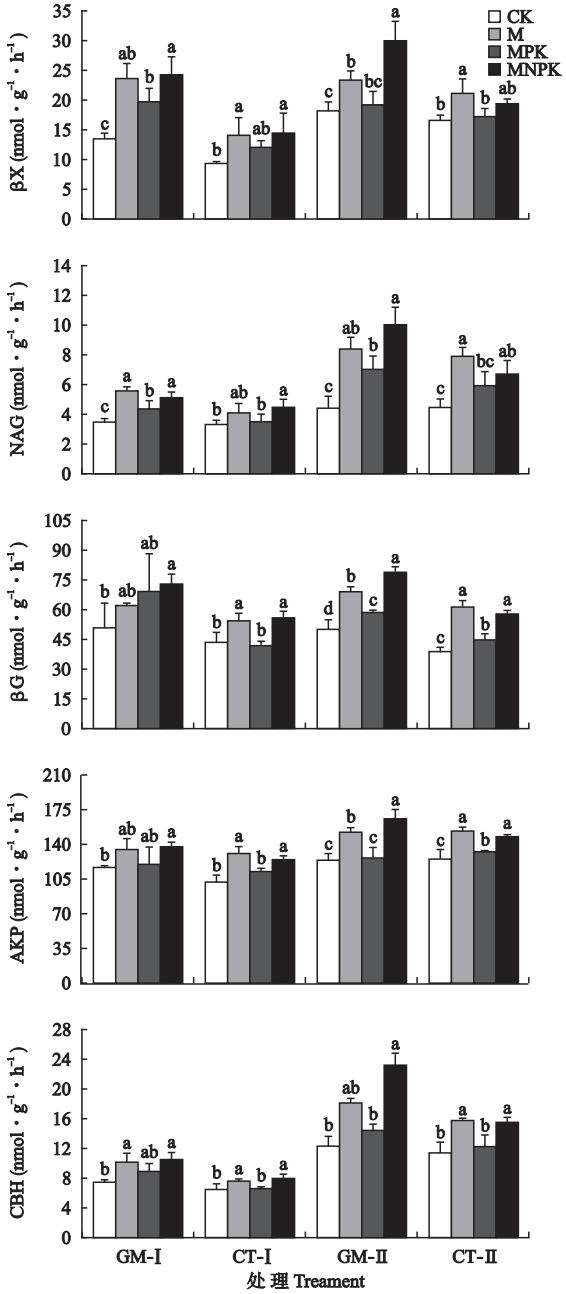


图 1　生草覆盖条件下不同肥料配施对土壤酶活性的影响

Fig.1　Effects of different fertilization regimes on soil enzyme activities under grass mulching.

Ⅰ：生草刈割前 Before the grass mowing；Ⅱ：生草刈割后 After the grass mowing. 下同 The same below. GM：生草覆盖 Grass mulch；CT：清耕处理 Clean tillage.

知，前两轴已能很好地反映土壤酶活性与环境因子的关系，且主要是由第 1 轴决定.生草覆盖条件下，各施肥处理的点处于土壤养分因子、土壤酶的箭头连线正向方向上，表明生草覆盖条件下各施肥处理与土壤养分和土壤酶呈正相关关系；清耕条件下各施肥处理的点处于土壤养分因子、土壤酶的箭头连线反向方向，表明清耕条件下各施肥处理与土壤养分和土壤酶呈负相关关系，且施肥处理的点在箭头

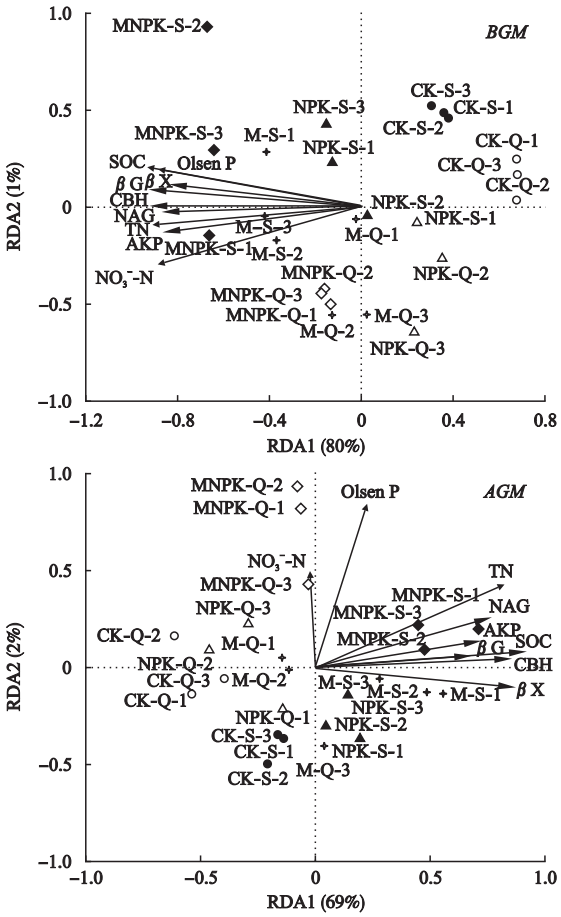


图 2　土壤环境因子与土壤酶活性的冗余分析（RDA）

Fig.2　Biplot of the first two axes of the redundancy analysis (RDA) for environmental factors associated with soil enzyme activities.

NO_3^--N：硝态氮 Nitrate nitrogen；Olsen P：有效磷 Available phosphorus；TN：全氮 Total nitrogen；SOC：土壤有机碳 Soil organic carbon；βX：β-1,4-木糖苷酶 β-1,4-xylosidase；βG：β-1,4-葡萄糖苷酶 β-1,4-glucosidase；AKP：碱性磷酸酶 Alkaline phosphatase；NAG：β-1,4-N-乙酰基氨基葡萄糖苷酶 β-1,4-N-acetyl-glucosaminidase；CBH：纤维二糖水解酶 Cellobiohydrolase.

上投影的长短总体呈 MNPK>M>NPK>CK 的趋势，投影越长代表对土壤酶活性的影响越大.

生草刈割前后全量养分和速效养分对土壤酶活性的影响存在差异.如图 2 所示，生草刈割前后全氮与 AKP 和 NAG、有机碳与 βX、βG、CBH 3 种碳循环相关的酶之间的箭头连线夹角很小且方向一致，均呈正相关关系，但刈割后全氮与 AKP 和 NAG 箭头的夹角要小于刈割前，刈割前有机碳与 βX、βG、CBH 3 种碳循环相关的酶之间夹角的大小顺序为 βG<CBH<βX，刈割后有机碳与 βX、βG、CBH 之间夹角的大小则发生变化，顺序为 βX<βG<CBH；刈割前后速效磷与 AKP、硝态氮与 NAG 之间都呈正相关关系，但刈割后速效磷与 AKP、硝态氮与 NAG 的相关性要大于刈割前.

3 讨 论

本研究表明,生草覆盖条件下有机无机配施的土壤含水量、速效养分、全量养分以及土壤酶活性显著高于其他处理(表 2 和图 1).总体上看,在生草刈割前,生草与果树产生了水分和养分的竞争,生草处理的含水量、速效磷、硝态氮含量显著低于清耕处理.李会科等[8]在黄土高原旱地苹果园生草对土壤贮水的影响研究中也表明,在 3—5 月春季阶段由于生草返青后生长迅速,蒸腾旺盛,生草与果树水分竞争强烈,导致失墒量增加,而在刈割覆盖后降低了生草与果树水分和速效养分的竞争.生草刈割后覆盖在行间又起到了防止地表径流[29]、避免空气和阳光接触地面、降低地表温度、减少了地面蒸发[30]的作用,提高了果园土壤水分含量.生草处理的硝态氮、速效磷含量显著高于清耕处理,说明生草活化有机态 N、P 的功能显著[31], 刈割前后冗余分析图(图 2)中速效磷与 AKP、硝态氮与 NAG 都存在显著相关关系也印证了这一点.随着生草腐解向土壤中输入了一定量的有机物质,生草处理的土壤全氮、有机碳含量显著提升.李会科等[9]在生草对黄土高原旱地苹果园土壤性状的影响研究中也发现,生草能提高果园土壤有机质含量,生草对果园土壤全氮的影响主要集中在 0~40 cm 土层,生草的前期土壤养分消耗大于积累,随着生草地被稳定群落的形成,全氮呈现恢复性增长,生草前期应重视对地被植物的施肥.土壤酶在一定程度上反映土壤养分转化的动态及土壤中生化反应的方向与强度,对维持土壤生态系统的碳、氮平衡起着重要作用.土壤酶主要来源于土壤微生物和植物根系分泌[20].本研究结果表明,生草覆盖下土壤酶活性显著高于清耕条件下,与苹果园[11,32]、桃园[33]、柑橘园[34]在生草条件下都增加了土壤碳、氮、磷循环相关酶活性的结论一致.刈割前后冗余分析图中生草处理均位于土壤环境因子和土壤酶活性因子箭头的正相关方向上,更直观地解释了生草对土壤质量的提升作用.

与 CK 处理相比,NPK 处理土壤酶活性、速效养分、全量养分等并没有显著增加,与有机物添加的 MNPK 和 M 处理相比反而有一定程度的下降,这与大多数研究结果[16,35]一致.本研究中,生草条件下刈割前 MNPK 处理与 NPK 处理相比,碳相关酶活性中只有 βX 活性显著高于 NPK 处理,而刈割后 βX、βG、CBH 活性均显著高于 NPK 处理,可能是由于 MNPK 处理的生草生物量高于 NPK 处理,在刈割覆盖后投入了更多的有机物料,积累了更多的腐殖质,降低了土壤容重,增大了土壤孔隙度,土壤的水热和通气状况良好,微生物活性增大[20].刈割前后 M 与 NPK 处理相比只有刈割后 βG 活性显著高于 NPK 处理,说明施用有机肥在带入大量有机物质和微生物的同时需要配合施用一定的化肥,微生物的生长发育受到养分供应的限制;清耕条件下刈割前后 MNPK 和 M 处理的 βG、CBH 活性均显著高于 NPK 和 CK 处理,可能是腐熟的有机肥中以纤维素的降解为主,纤维素以短链的纤维素多糖和纤维二糖为主[36].生草条件下刈割前后 MNPK 处理的 NAG 活性显著高于 NPK 处理,说明有机无机配施(与无机肥等氮量)可以通过为土壤微生物提供碳源,促进土壤氮素转化,进而提高氮肥利用效率[37].耿玉清等[28]在土壤磷酸酶活性及其与有机磷组分的相关性研究中表明,磷酸酶活性与土壤有机碳、有机磷以及活性、中活性和中稳性有机磷组分含量存在显著的相关性,与邱莉萍等[38]对碱性磷酸酶的研究结果一致.本研究通过冗余分析发现,AKP 的活性与有机碳具有显著的正相关性,因此可以通过提升土壤有机质的方法来增强土壤 AKP 活性.

参考文献

[1] Shaanxi Provincial Bureau of Statistics (陕西省统计局). Shaanxi Statistical Yearbook in 2015 [EB/OL]. (2016-01-20) [2017-03-02]. http://www.shaanxitj.gov.cn/upload/2016/tongjinianj/2015/indexch.htm (in Chinese)

[2] Food and Agriculture Organization of the United Nations. World Agricultural Statistics [EB/OL]. (2017-02-17) [2017-03-02]. http://www.fao.org/faostat/zh/#data/QC

[3] Yang Y (杨 玥), Tong Y-A (同延安), Lu Y-L (路永莉), *et al*. Evaluation on the situation of fertilization and soil fertility in apple fields in Shaanxi Province. *Agricultural Research in the Arid Areas* (干旱地区农业研究), 2016, **34**(5): 166-171 (in Chinese)

[4] Zheng X-C (郑小春), Lu H-J (卢海蛟), Che J-X (车金鑫), *et al*. Investigation of present yield and fertilization on Fuji apple in Baishui County. *Journal of Northwest A&F University* (Natural Science) (西北农林科技大学学报:自然科学版), 2011, **39**(9): 145-151 (in Chinese)

[5] Du Z-H (杜志辉), Fan H-K (樊红科), Lyu Z-F (吕周锋), *et al*. Effects of fertilization regime on growth, yield and quality of Fuji apple in Weibei highland. *Acta Agriculturae Boreali-Occidentalis Sinica* (西北农业学报), 2011, **20**(5): 121-125 (in Chinese)

[6] Zhao Z-P (赵佐平), Tong Y-A (同延安), Liu F (刘芬), *et al*. Assessment of current conditions of house-

hold fertilization of apples in Weibei Plateau. *Chinese Journal of Eco-Agriculture* (中国生态农业学报), 2012, **20**(8): 1003-1009 (in Chinese)

[7] Gao Y-M (高义民), Tong Y-A (同延安), Lu Y-L (路永莉), *et al*. Effects of soil available nutrients and long-term fertilization on yield of Fuji apple orchard of Weibei Area in Shaanxi, China. *Acta Horticulturae Sinica* (园艺学报), 2013, **40**(4): 613-622 (in Chinese)

[8] Li H-K (李会科), Zhang G-J (张广军), Zhao Z-Y (赵政阳), *et al*. Effects of growing different herbages on soil water-holding of a non-irrigated apple orchard in the weibei area of the Loess Plateau. *Acta Agrestia Sinica* (草地学报), 2007, **15**(1): 76-81 (in Chinese)

[9] Li H-K (李会科), Zhang G-J (张广军), Zhao Z-Y (赵政阳), *et al*. Effects of interplanted herbages on soil properties of a non-irrigated apple orchards in the Loess Plateau. *Acta Prataculturae Sinica* (草业学报), 2007, **16**(2): 32-39 (in Chinese)

[10] Li H-K (李会科), Zhang G-J (张广军), Zhao Z-Y (赵政阳), *et al*. Effects of different herbages on soil quality characteristics of non-irrigated apple orchards in Weibei Loess Plateau. *Scientia Agricultura Sinica* (中国农业科学), 2008, **41**(7): 2070-2076 (in Chinese)

[11] Qian X, Gu J, Pan H, *et al*. Effects of living mulches on the soil nutrient contents, enzyme activities, and bacterial community diversities of apple orchard soils. *European Journal of Soil Biology*, 2015, **70**: 23-30

[12] Merwin IA, Stiles WC, Van Es HM. Orchard groundcover management impacts on soil physical properties. *Journal of the American Society for Horticultural Science*, 1994, **119**: 216-222

[13] Rodrigues MÂ, Correia CM, Claro AM, *et al*. Soil nitrogen availability in olive orchards after mulching legume cover crop residues. *Scientia Horticulturae*, 2013, **158**: 45-51

[14] Hartwig NL, Ammon HU. Cover crops and living mulches. *Weed Science*, 2003, **50**: 688-699

[15] Trap J, Riah W, Akpa-Vinceslas M, *et al*. Improved effectiveness and efficiency in measuring soil enzymes as universal soil quality indicators using microplate fluorimetry. *Soil Biology and Biochemistry*, 2012, **45**: 98-101

[16] Fan M-Z (范淼珍), Yin C (尹　昌), Fan F-L (范分良), *et al*. Effects of different long-term fertilization on the activities of enzymes related to carbon, nitrogen, and phosphorus cycles in a red soil. *Chinese Journal of Applied Ecology* (应用生态学报), 2015, **26**(3): 833-838 (in Chinese)

[17] Li T-T (李涛涛), Zhai B-N (翟丙年), Li Y-G (李永刚), *et al*. Effect of fertilizer type on growth and yield of Fuji apple in Weibei dry region of Shaanxi. *Journal of Fruit Science* (果树学报), 2013, **30**(4): 591-596 (in Chinese)

[18] He W-X (和文祥), Zhu M-E (朱铭莪). Relationship between urease activity and fertility of soil in Shaanxi Province. *Acta Pedologica Sinica* (土壤学报), 1997, **34**(4): 392-398 (in Chinese)

[19] Badiane NNY, Chotte JL, Pate E, *et al*. Use of soil enzyme activities to monitor soil quality in natural and improved fallows in semi-arid tropical regions. *Applied Soil Ecology*, 2001, **18**: 229-238

[20] Wang L-D (王理德), Wang F-L (王方琳), Guo C-X (郭春秀), *et al*. Review: Progress of soil enzymology. *Soils* (土壤), 2016, **48**(1): 12-21 (in Chinese)

[21] Burns RG, Deforest JL, Marxsen J, *et al*. Soil enzymes in a changing environment: Current knowledge and future directions. *Soil Biology & Biochemistry*, 2013, **58**: 216-234

[22] Liu Y, Gao M, Wu W, *et al*. The effects of conservation tillage practices on the soil water-holding capacity of a non-irrigated apple orchard in the Loess Plateau, China. *Soil & Tillage Research*, 2013, **130**: 7-12

[23] Huang J, Wang J, Zhao X, *et al*. Effects of permanent ground cover on soil moisture in jujube orchards under sloping ground: A simulation study. *Agricultural Water Management*, 2014, **138**: 68-77

[24] Marx MC, Wood M, Jarvis SC. A microplate fuorimetric assay for the study of enzyme diversity in soils. *Soil Biology & Biochemistry*, 2001, **33**: 1633-1640

[25] Trap J, Riah W, Akpa-Vinceslas M, *et al*. Improved effectiveness and efficiency in measuring soil enzymes as universal soil quality indicators using microplate fluorimetry. *Soil Biology & Biochemistry*, 2012, **45**: 98-101

[26] Cui Y-H (崔艳荷), Zhang W (张　威), He H-B (何红波), *et al*. Effects of nitrogen addition on transformation of amino sugars in forest soil. *Chinese Journal of Ecology* (生态学杂志), 2016, **35**(4): 960-965 (in Chinese)

[27] Zhang W (张　威), Zhang M (张　明), Bai Z (白震), *et al*. Research advances in soil chitinase. *Chinese Journal of Soil Science* (土壤通报), 2007, **38**(3): 569-575 (in Chinese)

[28] Geng Y-Q (耿玉清), Bai C-X (白翠霞), Zhao G-L (赵广亮), *et al*. Soil phosphatase activity and its correlation with composition of organic phosphorus. *Journal of Beijing Forestry University* (北京林业大学学报), 2008, **30**(suppl.2): 139-143 (in Chinese)

[29] Celette F, Gaudin R, Gary C. Spatial and temporal changes to the water regime of a Mediterranean vineyard due to the adoption of cover cropping. *European Journal of Agronomy*, 2008, **29**: 153-162

[30] Pradel E, Pieri P. Influence of a grass layer on vineyard soil temperature. *Australian Journal of Grape and Wine Research*, 2000, **6**: 59-67

[31] Zhang M (张　猛), Zhang J (张　健), Xu X (徐雄), *et al*. Effects of soil management ways on soil properties of an artificial fruit-grass ecosystem. *Scientia Silvae Sinicae* (林业科学), 2006, **42**(8): 44-49 (in Chinese)

[32] Jia M-L (贾曼莉), Guo H (郭　宏), Li H-K (李会科), *et al*. Mineralization of soil organic carbon and its relationship with soil enzyme activities in apple orchard in Weibei. *Environmental Science* (环境科学), 2014,

35(7): 2777-2784 (in Chinese)
[33] Ramos ME, Benítez E, García PA, *et al*. Cover crops under different managements vs. frequent tillage in almond orchards in semiarid conditions: Effects on soil quality. *Applied Soil Ecology*, 2010, **44**: 6-14
[34] Wang P, Wang Y, Wu QS. Effects of soil tillage and planting grass on arbuscular mycorrhizal fungal propagules and soil properties in citrus orchards in southeast China. *Soil & Tillage Research*, 2016, **155**: 54-61
[35] Lu H-F (陆海飞), Zheng J-W (郑金伟), Yu X-C (余喜初), *et al*. Microbial community diversity and enzyme activity of red paddy soil under long-term combined inorganic-organic fertilization. *Journal of Plant Nutrition and Fertilizer* (植物营养与肥料学报), 2015, **21**(3): 632-643 (in Chinese)
[36] Yu Y (于 跃), Zhang J (张 剑). Research progress in degradation of cellulose by cellulase. *Chemistry* (化学通报), 2016, **79**(2): 118-122 (in Chinese)
[37] Duan Y, Xu M, Gao S, *et al*. Nitrogen use efficiency in a wheat-corn cropping system from 15 years of manure and fertilizer applications. *Field Crops Research*, 2014, **157**: 47-56
[38] Qiu L-P (邱莉萍), Liu J (刘 军), Wang Y-Q (王益权), *et al*. Research on relationship between soil enzyme activities and soil fertility. *Journal of Plant Nutrition and Fertilizer* (植物营养与肥料学报), 2004, **10**(3): 277-280 (in Chinese)

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Gong Q-L, Zhai B-N, Zheng W, *et al*. Effects of grass cover combined with different fertilization regimes on soil nutrients and enzyme activities in apple orchard in Weibei dryland, China. *Chinese Journal of Applied Ecology*, 2018, **29**(1): 205-212 (in Chinese)