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水旱轮作体系中长期施肥对作物产量及紫色土有机碳的影响

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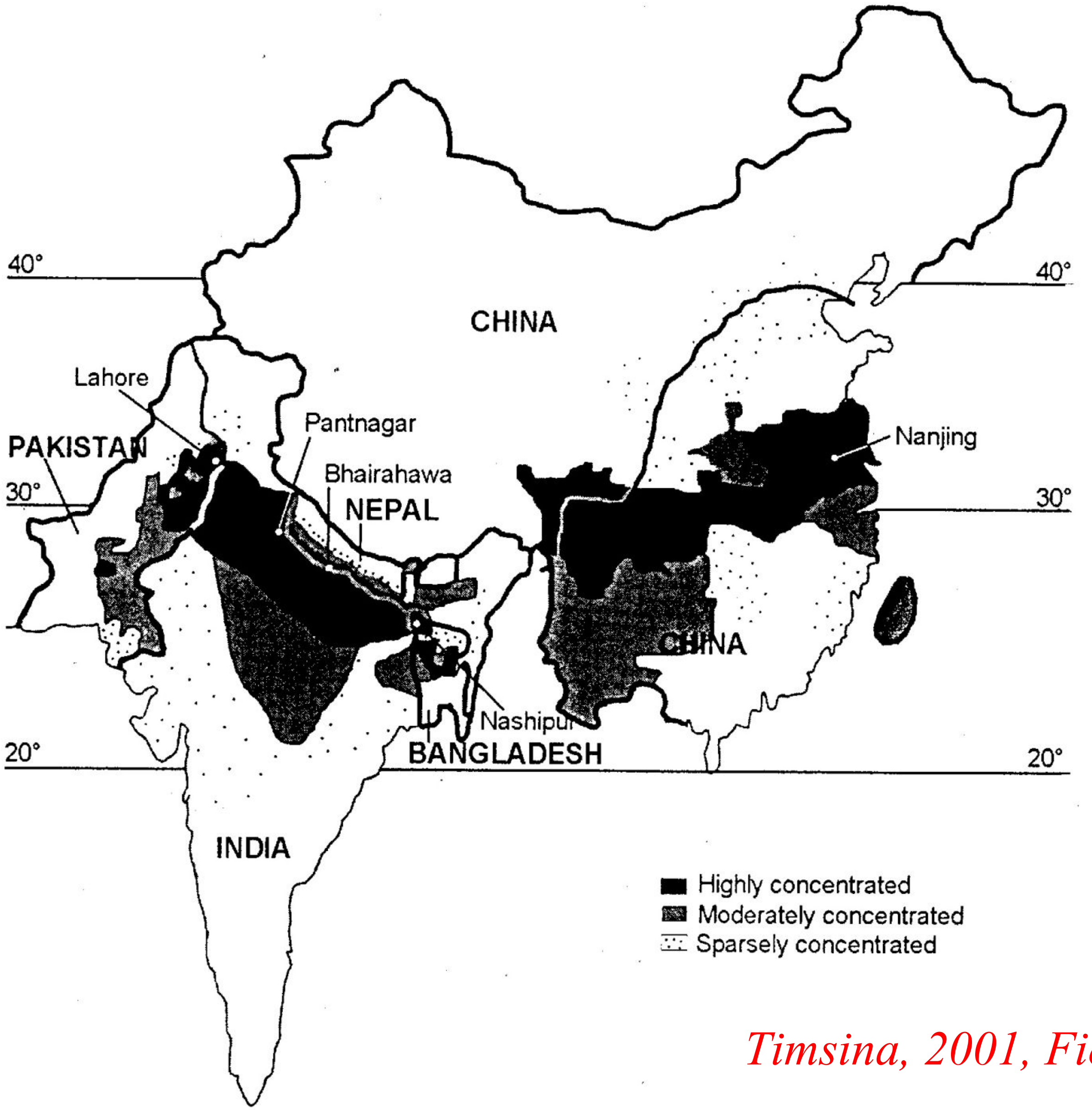
主要内容

- 研究背景
- 试验介绍
- 结果与分析
- 展望

水旱轮作（稻麦轮作）体系分布



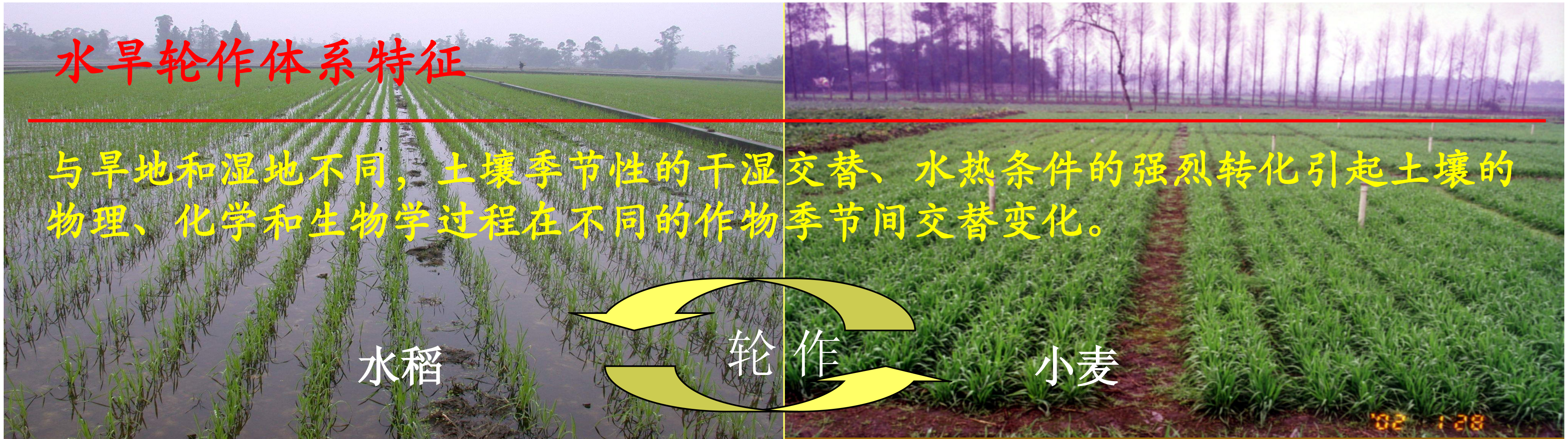
主要分布在东亚和南亚；

中国主要分布在长江流域

Timsina, 2001, Field Crops Research

水旱轮作体系特征

与旱地和湿地不同，土壤季节性的干湿交替、水热条件的强烈转化引起土壤的物理、化学和生物学过程在不同的作物季节间交替变化。



Chemical

水稻	小麦
$CH_4 \leftarrow SOC$	$SOC \rightarrow CO_2$
$NH_4\text{-}N \leftarrow SOC$	$SOC \rightarrow NH_4\text{-}N \rightarrow NO_3\text{-}N$
$NH_4\text{-}N \leftarrow$ Fertilizer	Fertilizer $\rightarrow NH_4\text{-}N \rightarrow NO_3\text{-}N$
$NH_3, N_2O \leftarrow NO_{3-}(NH_{4+})$	$NO_{3-}(NH_{4+}) \rightarrow NH_3$
$H_2PO_4^- \leftarrow Fe^{2+} \leftarrow Fe^{3+}$; $H_2PO_4^- \leftarrow$ Ca-P+ H_2O ; $M^{3+}(M^{2+})PO_4$	$M^{3+}(M^{2+})PO_4 \leftarrow Fe^{3+}\ Al^{3+}\ Ca^{2+}\ Mn^{3+}\ Mn^{4+}\ H_2PO_4^-$
$Fe^{2+} \leftarrow Fe^{3+}$	$Fe^{2+} \rightarrow Fe^{3+}$
$Mn^{2+} \leftarrow Mn^{3+}, Mn^{4+}$	$Mn^{2+} \rightarrow Mn^{3+}, Mn^{4+}$

Physical 微团粒，大容重，通气空隙少 | 团粒，小容重，通气空隙多

Biological 厌气微生物 | 好气微生物

水旱轮作体系作物产量变化趋势

Location	No. of data set	Average yield change (Mg ha^{-1} per year)	Average[a] yield (Mg ha^{-1})	No. of positive and negative trends[b]	
				Positive	Negative
Rice					
IGP2	6	−0.002	6.04	2 (0)	4 (2)
IGP3	6	−0.044	5.00	2 (1)	4 (2)
IGP4	9	−0.056	3.69	4 (0)	5 (4)
IGP5	4	0.007	3.22	2 (0)	2 (0)
Non-IGP	7	0.022	4.11	4 (1)	3 (0)
China	4	−0.036	6.43	2 (0)	2 (0)
Total	36	−0.023	4.63	16 (2)	20 (8)
Wheat					
IGP2	6	0.090	4.70	6 (1)	0
IGP3	6	−0.002	3.82	3 (1)	3 (0)
IGP4	8	−0.036	2.91	1 (0)	7 (1)
IGP5	3	0.044	3.14	3 (0)	0
Non-IGP	7	0.000	2.73	3 (1)	4 (1)
China	3	−0.040	3.82	1 (0)	2 (0)
Total	33	0.007	3.47	17 (3)	16 (2)
System[c]					
IGP2	6	0.070	10.69	3 (1)	3 (1)
IGP3	6	−0.042	8.81	2 (2)	4 (2)
IGP4	8	−0.101	7.06	1 (0)	7 (3)
IGP5	3	0.050	7.39	2 (0)	1 (0)
Non-IGP	7	0.023	6.84	5 (0)	2 (0)
China	3	−0.092	12.39	0	3 (0)
Total	33	−0.019	8.50	13 (3)	20 (6)

[a] Average yield for the entire duration of the experiment as given in Table 1.
[b] Numbers in parentheses indicate the number of LTEs with time trends that are statistically significant at the 5% level.
[c] Rice–rice–wheat systems are included in IGP4, IGP5 and China.

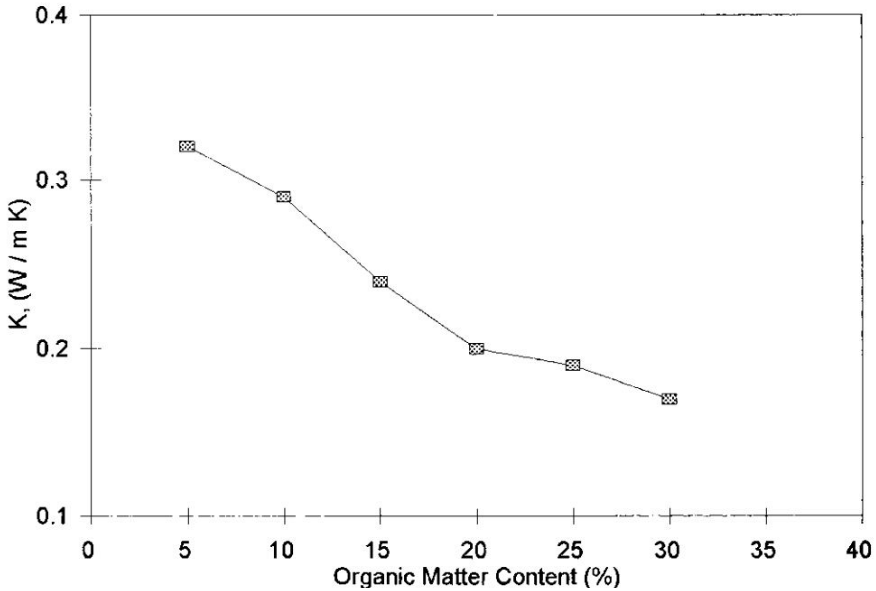
产量下滑可能原因

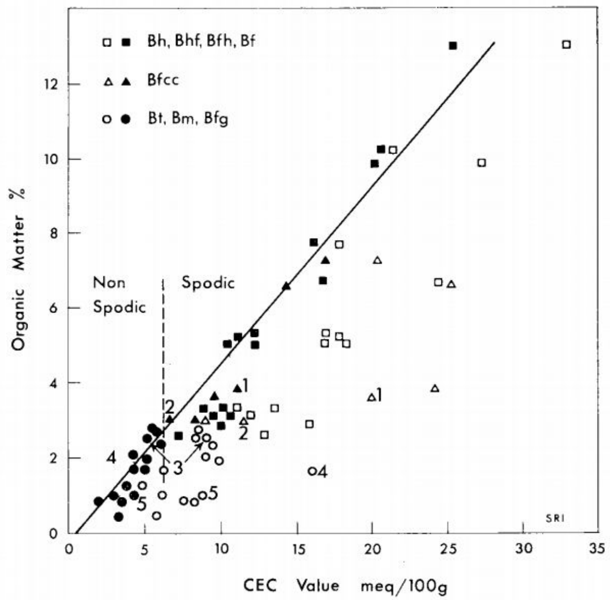
Possible causes of yield decline in various LTEs

LTEs	Causes of yield decline
Bhairahwa 1	Delay in sowing (wheat); decline in soil N, available P, K and Zn
Bhairahwa 2	Delay in sowing (wheat); decline in soil C, available P and K
Karnal 1	Decline in soil K
Ludhiana 1	Decrease in solar radiation; in crease in minimum temperature, decline in soil C, N, and K
Pantnagar 1	Decline in soil C and N
Pantnagar 4	Decline in soil available P and K
Pusa	Decline in soil K and available Zn
Tarahara	Decline in soil available P and K

Ladha et al，2001, Field Crops Research

有机碳与土壤肥力的关系





Sample, depth	Subsample	Carbon (g m^{-2})	Nitrogen (g m^{-2})	Organic P (g m^{-2})
Fresh litter, 0–1 cm	Total	65	1.6	0.02
Org. layer, 1–21 cm	Total	6,930	315	12.1†
Min. soil, 21–36 cm	Total	5,145	239	7.7
	Coarse C	2,835	116	4.9
	Clay + silt	2,310	123	2.8
Min. soil, 36–60 cm	Total	5,799	295	9.6
	Soil <0.5 mm	3,274	246	6.2
	Coarse C	696	118	1.4
	Clay + silt	2,578	128	4.8
	Nodules >0.5 mm	2,525	49	3.4
Total to 60 cm		17,939	850	22.7

Tiessen et al., 1994, Nature

有机碳与作物产量的关系

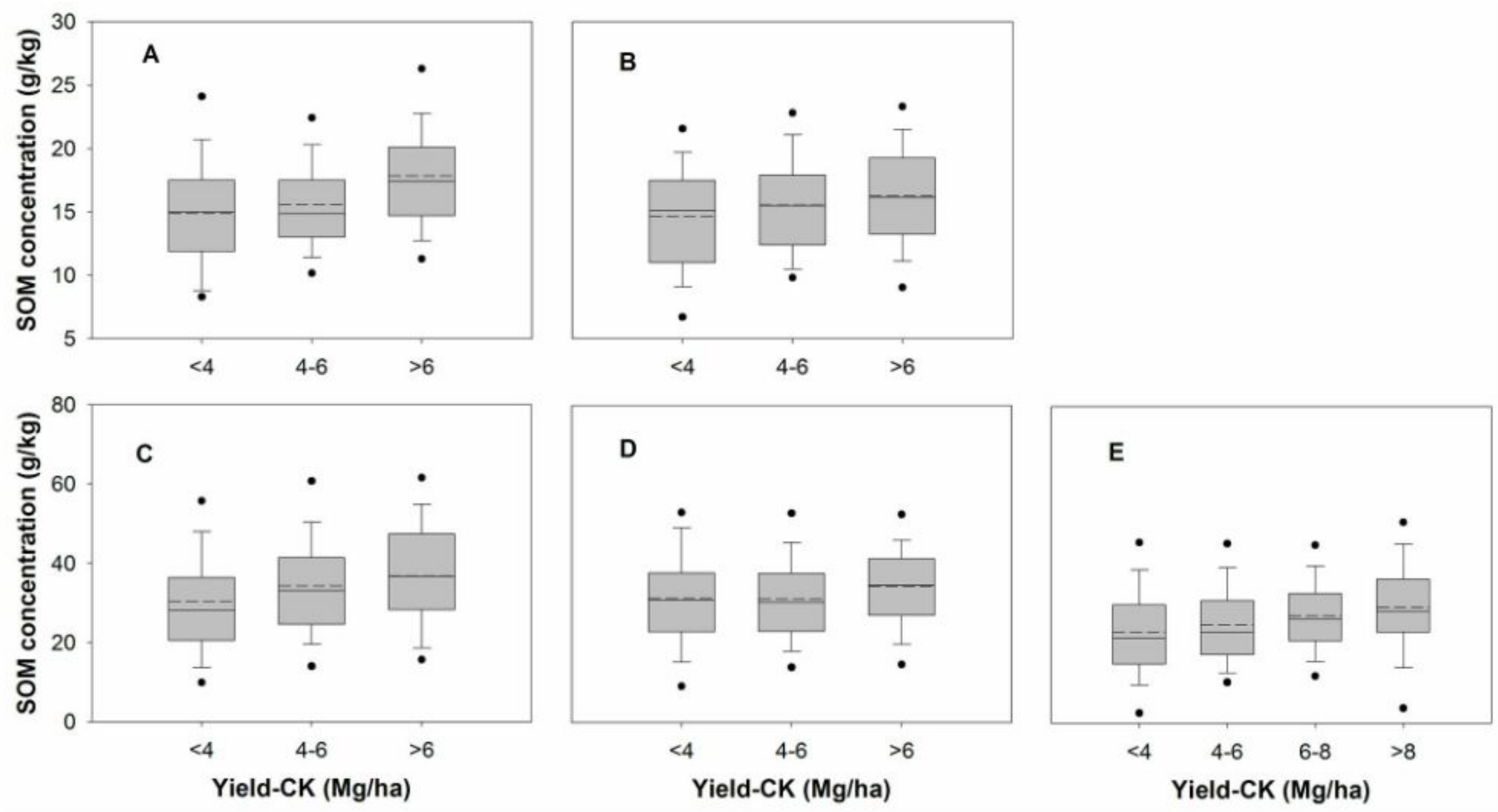
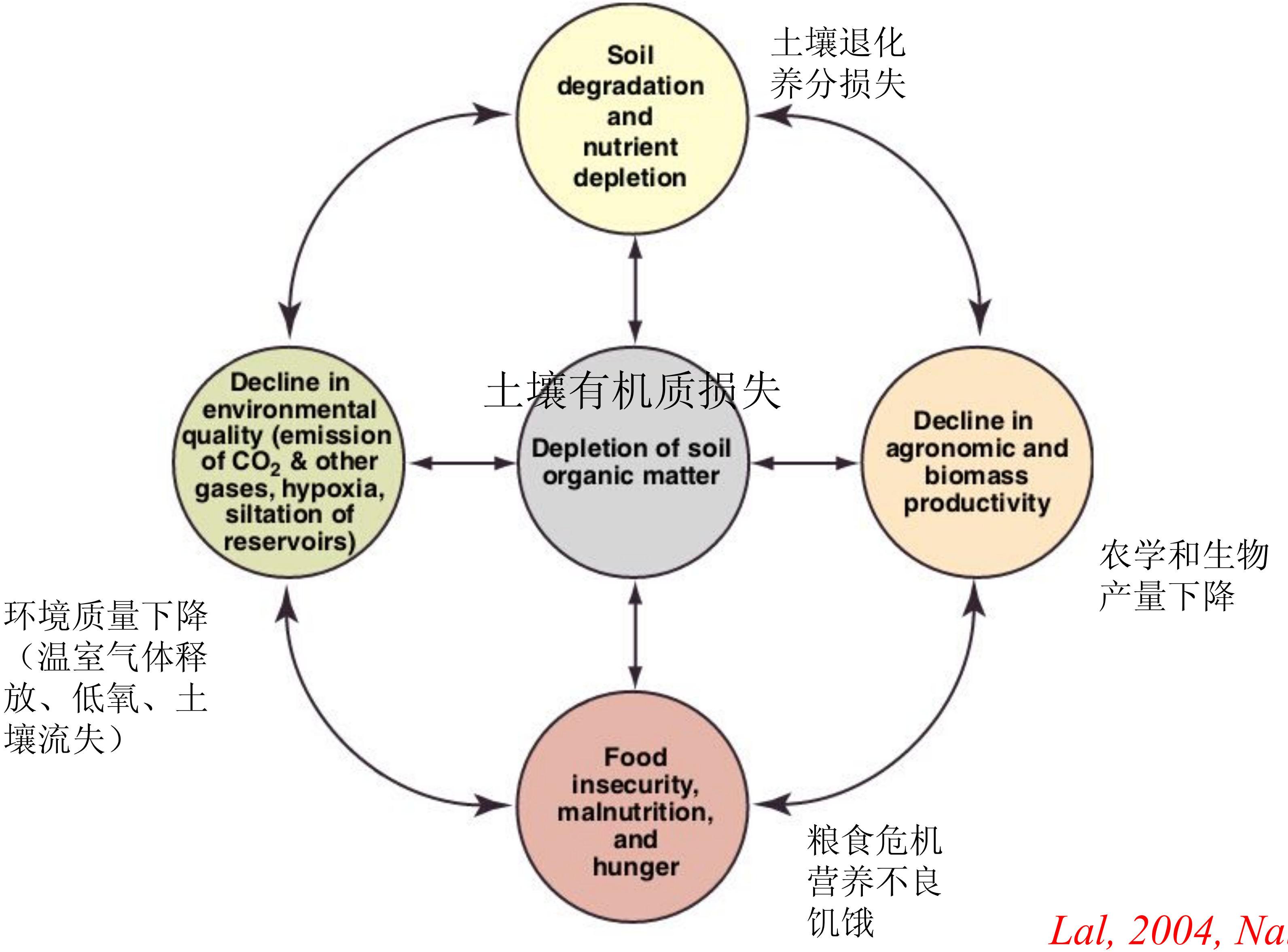


Figure 1. Relations between soil organic matter (SOM) concentrations and grain yield without fertilizer addition for on-farm trials (Yield-CK) in 5 major irrigated cereal-based cropping systems in China. (a) winter wheat in north China (n=354); (b) summer maize in north China (n=425) (c) early rice in south of China (n=697); (d) late rice in south of China (n=688); (e) single rice in Yangtze River Basin (n=2474). Solid and dashed lines in this figure indicate median and mean yield, respectively. The box boundaries indicate upper and lower quartiles, the whisker caps indicate 90th and 10th percentiles, and the circles indicate the 95th and 5th percentiles.

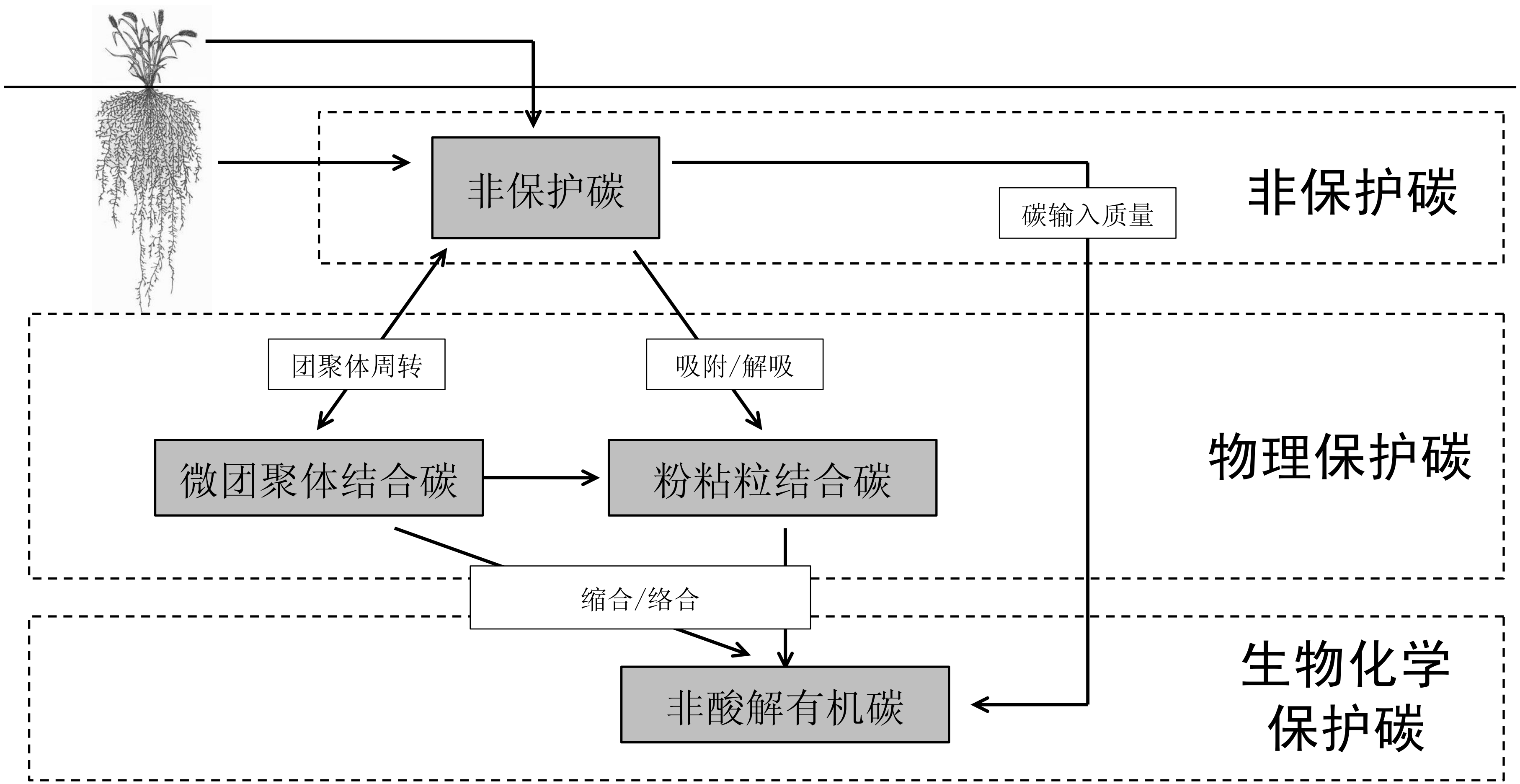
Fan et al., 2013, PIOS one
Pan et al., 2009, Agriculture, Ecosystems and Environment

土壤有机碳与全球气候变化及粮食安全



Lal, 2004, Nature

土壤有机碳的保护机制



Six et al., 2002, Plant & Soil

土壤有机碳的分组方法

1900s
化学分组----研究腐殖质
富啡酸、胡敏酸、胡敏素

1930s
团聚体分组----研究土壤结构（团聚体）
胶散分组，结合态分组-----研究土壤有机无机复合体

1960s
颗粒分组，密度分组

粒径+密度分组
化学+密度分组----研究土壤有机物无机复合体

1990s
- Aggregate+size+density(Elliott, 1991 ,Agriculture, Ecosystems and Environment)
- POM (Cambardella and Elliott, 1992, Soil Sci. Soc. Am. J)
- aggregate+POM (Cambardella and Elliott, 1993, Soil Sci. Soc. Am. J)
- Labile Carbon+CMI(Lefroy and Blair, 1993, Plant & Soil; Blair and Lefroy, 1995, Australian journal of agricultural research)
- fPOM/oPOM (Golchin et al., 1994, Australian Journal of Soil Research)
- aggregate+fPOM+iPOM (Jastrow, 1996, SBB)
- Six et al., 1998, Soil Science Society of America Journal
- Six et al., 2002, Soil Science Society of America Journal

- 存在位置
- 存在类型
- 固碳途径
- 影响因子

主要内容

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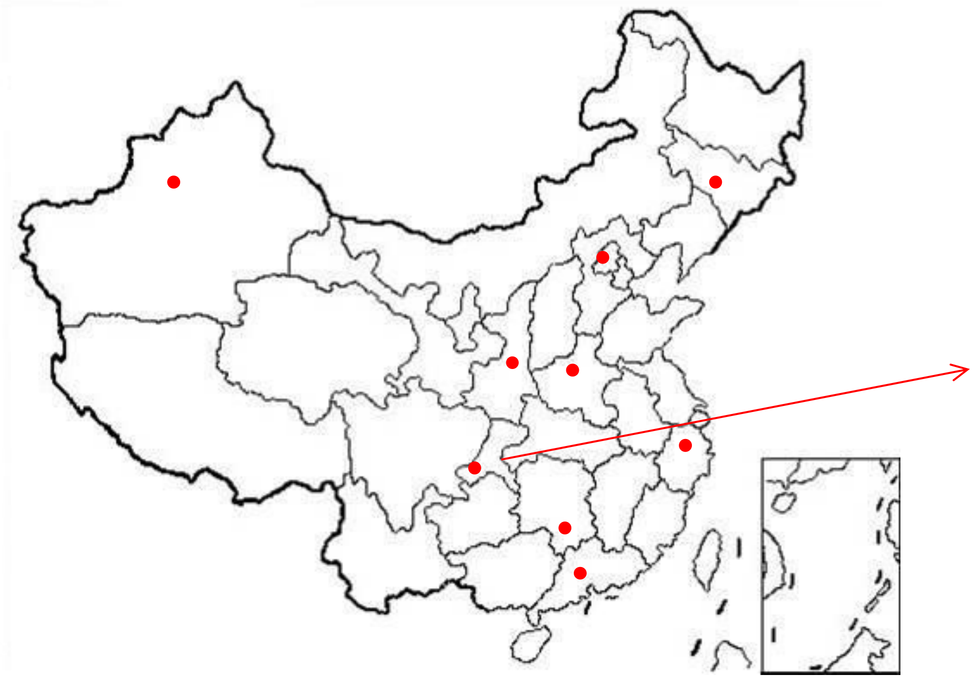
长期定位试验概况



国家土壤肥力与肥料效应监测基地网

试验地点： 重庆市西南大学

地理位置： 东经106°26′，北纬30°26′

海拔： 266.3m

地形地貌： 方山浅丘坳谷地形

土壤类型： 中性紫色水稻土

种植制度： 水稻-小麦

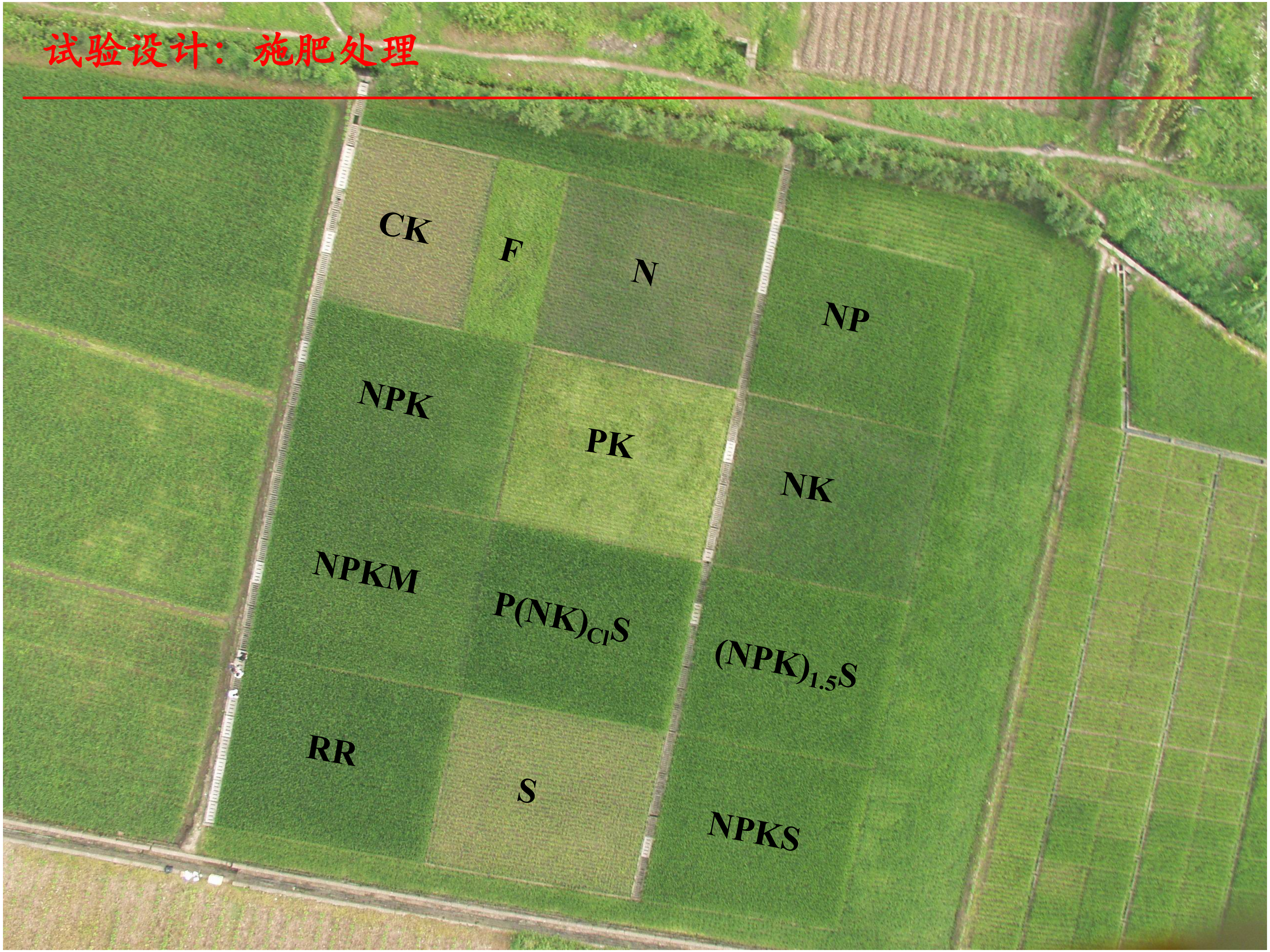
试验时间： 1989年秋匀地、1991年秋开始

平均温度： 18.3 ℃

降雨量： 1105.4mm

年日照： 1293.6h

试验设计：施肥处理



试验设计：肥料用量

treatment	chemical fertilizer in rice season (kg/ha)			chemical fertilizer in wheat season (kg/ha)			pen manure (t/ha)	rice straw (t/ha)
	N	P_2O_5	K_2O	N	P_2O_5	K_2O		
CK	0	0	0	0	0	0	0	0
N	135(150)	0	0	150	0	0	0	0
NP	135(150)	60(75)	0	150	60(75)	0	0	0
NK	135(150)	0	60(75)	150	0	60(75)	0	0
PK	0	60(75)	60(75)	0	60(75)	60(75)	0	0
NPK	135(150)	60(75)	60(75)	150	60(75)	60(75)	0	0
S	0	0	0	0	0	0	0(22.5)	7.5(0)
NPKM	135(150)	60(75)	60(75)	150	60(75)	60(75)	22.5	0
$P(NK)_{Cl}S$	135(150)	60(75)	60(75)	150	60(75)	60(75)	0(22.5)	7.5(0)
$(NPK)_{1.5}S$	202(225)	90(112.5)	112.5(90)	225	112.5(90)	112.5(90)	0(22.5)	7.5(0)
NPKS	135(150)	60(75)	60(75)	150	60(75)	60(75)	0	7.5

- M and S denote pen manure and rice straw respectively
- Fertilizer rate from rice season of 1991 to wheat season of 1996 is recorded as numbers within parentheses while since then as numbers outside

测定项目及方法

1991-2013年历年水稻季

产量：

有机碳： 高温外热重铬酸钾氧化容量法

碳投入： 参数估算

2013年水稻季

易氧化有机碳： 高锰酸钾氧化比色法

颗粒碳有机碳： $(NaPO_3)_6$-过筛-测定有机碳

有机无机复合态-钙镁键结合态-铁铝键结合态有机碳： 重液-$NaSO_4$-$NaOH$+$Na_4P_2O_7$-测定有机碳

主要内容

- ➢研究背景
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- ➢展望

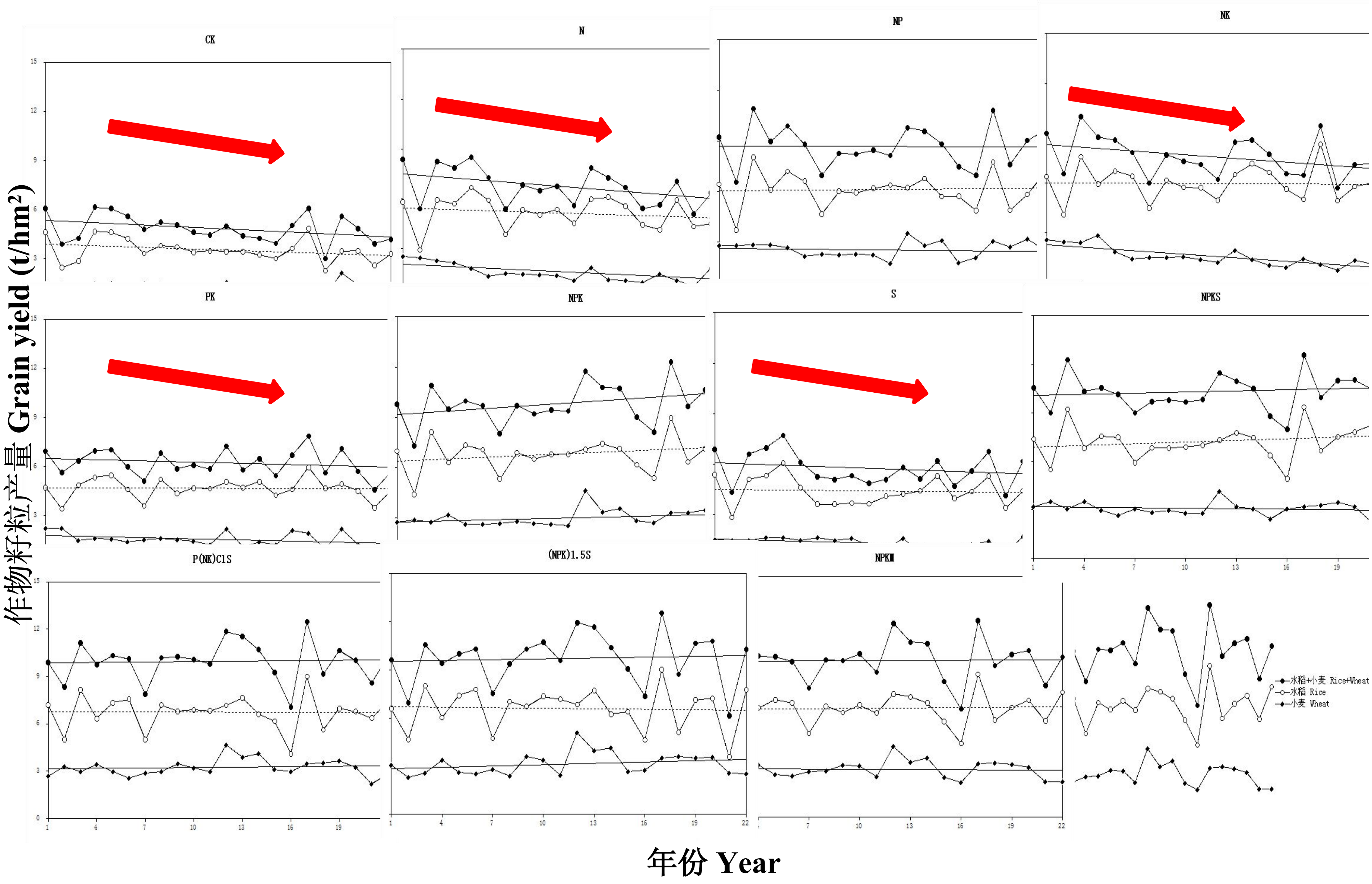
长期施肥对水稻产量的影响

处理Treatment	水稻 Rice					
	M		SD	Max	CV	SYI
CK	3.54	g	0.71	4.84	20.0	0.58
N	5.10	e	0.93	6.69	18.3	0.62
NP	6.14	cd	0.99	8.05	16.2	0.64
NK	5.98	d	1.05	8.34	17.6	0.59
PK	4.66	ef	0.61	5.94	13.2	0.68
NPK	6.85	ab	0.98	8.98	14.3	0.65
S	4.41	f	0.82	6.08	18.7	0.59
NPKS	7.23	a	1.05	9.34	14.6	0.66
$P(NK)_{Cl}S$	6.73	ab	1.09	9.01	16.2	0.63
$(NPK)_{1.5}S$	6.59	bc	1.33	9.01	20.2	0.58
NPKM	6.78	ab	1.06	8.91	15.6	0.64

长期施肥对小麦产量的影响

处理Treatment	小麦 Wheat					
	M		SD	Max	CV	SYI
CK	1.30	c	0.30	2.13	23.0	0.47
N	1.56	c	0.49	2.57	31.3	0.42
NP	2.54	b	0.48	3.55	19.0	0.58
NK	1.55	c	0.57	2.83	37.1	0.34
PK	1.55	c	0.41	2.22	26.3	0.51
NPK	3.03	a	0.50	4.65	16.5	0.54
S	1.30	c	0.34	1.75	25.9	0.55
NPKS	3.07	a	0.40	4.16	13.0	0.64
$P(NK)_{Cl}S$	3.23	a	0.54	4.67	16.7	0.58
$(NPK)_{1.5}S$	3.13	a	0.71	5.10	22.7	0.47
NPKM	2.98	a	0.53	4.40	17.8	0.56

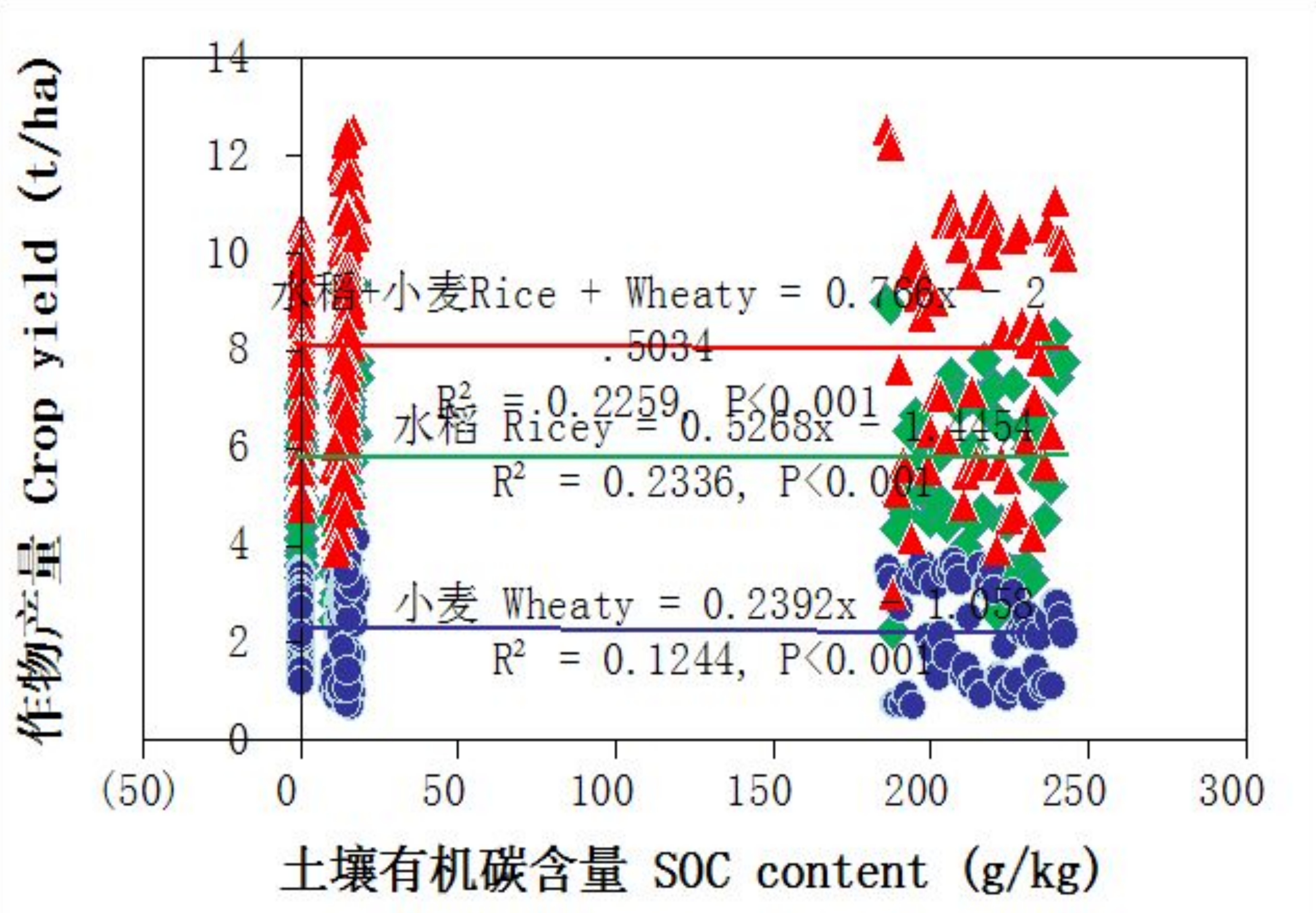
长期施肥对产量变化趋势的影响



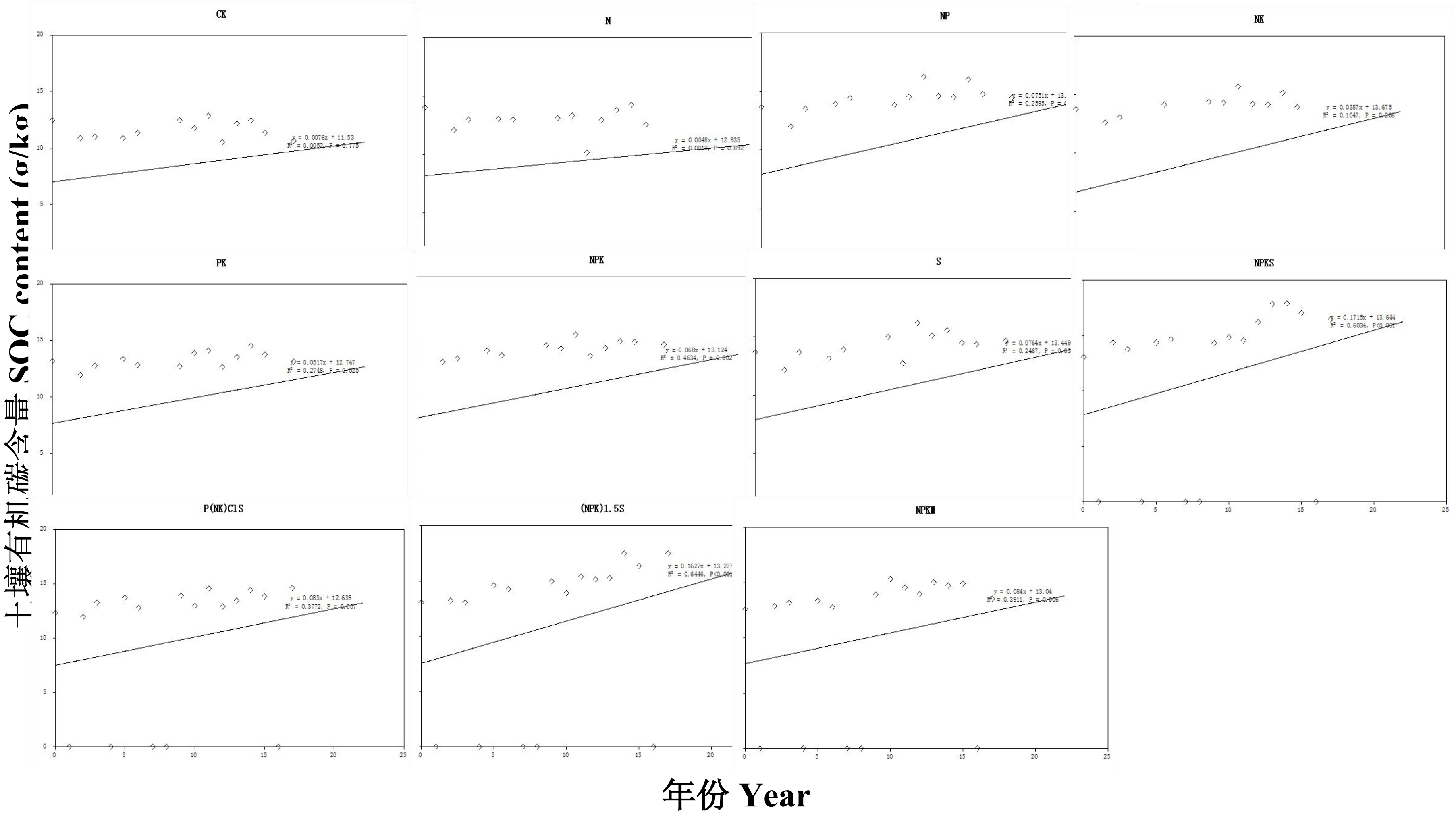
施肥对作物产量的影响

编号 ID	处理 Treatment	水稻产量年均变化 Annual change of rice yield			小麦产量年均变化 Annual change of wheat yield		
		kg/hm²	%	P	kg/hm²	%	P
1	CK	-34.6	-0.98	0.150	-11.8	-0.91	0.248
2	N	-31.7	-0.62	0.322	-48.6	-3.12	0.001*
3	NP	7.0	0.11	0.839	-10.3	-0.41	0.540
4	NK	-3.4	-0.06	0.926	-72.7	-4.70	0.000*
5	PK	-2.6	-0.06	0.905	-23.1	-1.49	0.093
6	NPK	44.8	0.65	0.180	23.5	0.78	0.169
7	S	-11.2	-0.25	0.697	-26.6	-2.05	0.014*
8	NPKS	34.2	0.47	0.347	-10.7	-0.35	0.437
9	$P(NK)_{Cl}S$	-1.3	-0.02	0.972	8.9	0.28	0.643
10	$(NPK)_{1.5}S$	-9.2	-0.14	0.843	26.7	0.85	0.275
11	NPKM	9.2	0.14	0.803	-4.8	-0.16	0.794

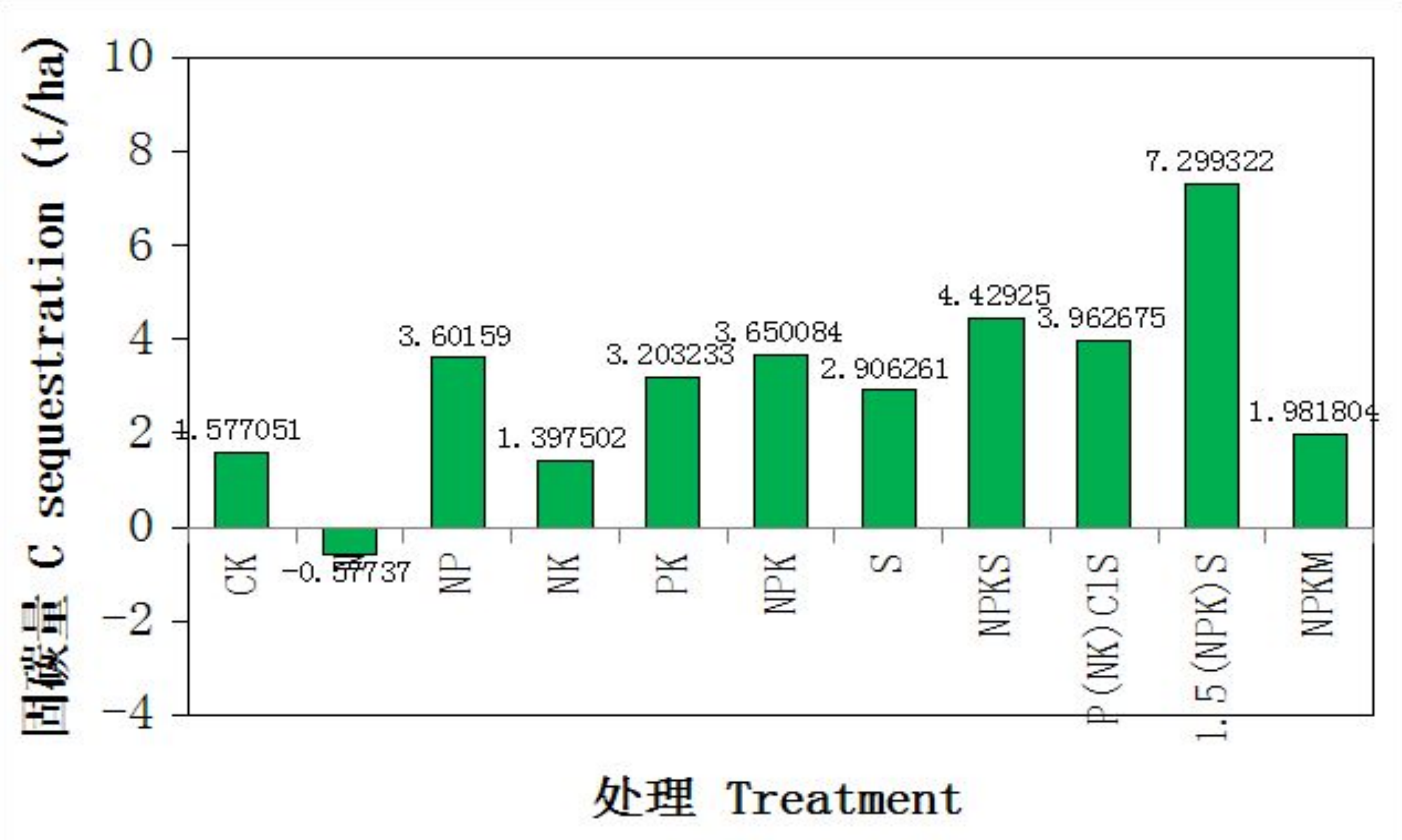
作物产量与土壤有机碳的关系



施肥对土壤有机碳的影响



长期施肥对土壤固碳的影响



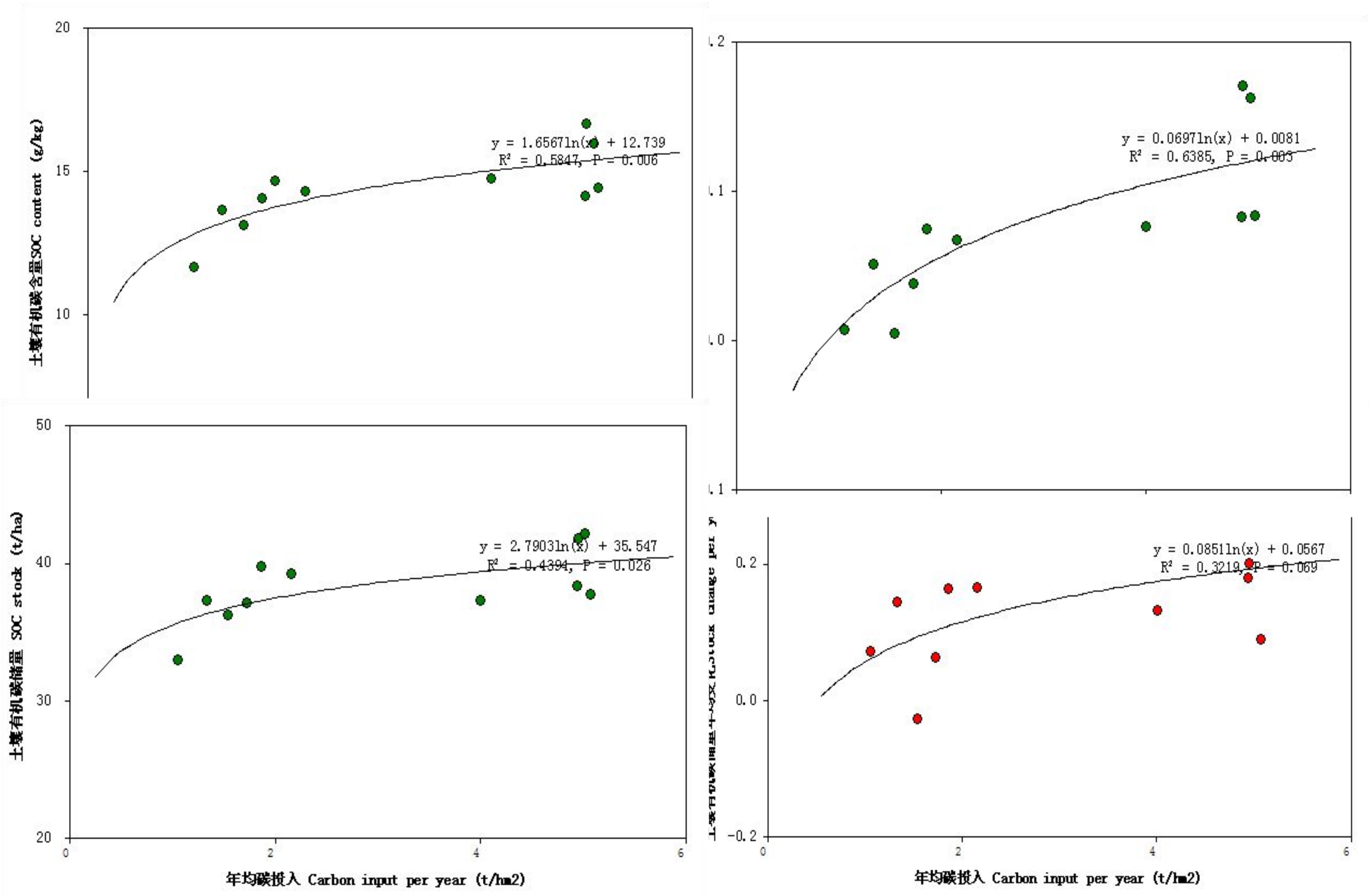
长期施肥对土壤有机碳含量和储量的影响

处理 Treatment	土壤有机碳含量 SOC (g/kg)				土壤容重 DB (g/cm³)				土壤有机碳储量 Stock (t/ha)			
	1991-1995	2009-2013	△	%	1991-1995	2009-2013	△	%	1991-1995	2009-2013	△	%
CK	11.4	11.7	0.23	2.0	1.38	1.42	0.04	2.91	31.4	33.0	1.58	5.0
N	13.1	13.1	0.07	0.6	1.41	1.38	-0.03	-2.13	36.8	36.2	-0.58	-1.6
NP	13.1	14.7	1.62	12.4	1.39	1.36	-0.03	-2.17	36.2	39.8	3.60	10.0
NK	13.2	14.1	0.93	7.1	1.36	1.32	-0.04	-2.94	35.8	37.2	1.40	3.9
PK	12.6	13.7	1.08	8.6	1.36	1.37	0.01	0.74	34.2	37.4	3.20	9.4
NPK	13.0	14.3	1.33	10.3	1.37	1.37	0.00	0.00	35.6	39.2	3.65	10.3
S	13.2	14.8	1.57	11.9	1.31	1.27	-0.04	-3.07	34.4	37.3	2.91	8.4
NPKS	13.7	16.7	2.91	21.2	1.36	1.26	-0.11	-7.72	37.4	41.8	4.43	11.8
$P(NK)_{Cl}S$	12.5	14.2	1.65	13.1	1.38	1.36	-0.02	-1.45	34.4	38.4	3.96	11.5
$(NPK)_{1.5}S$	13.1	16.0	2.86	21.8	1.33	1.32	-0.01	-0.75	34.9	42.2	7.30	20.9
NPKM	12.9	14.4	1.54	12.0	1.39	1.31	-0.08	-5.76	35.8	37.8	1.98	5.5

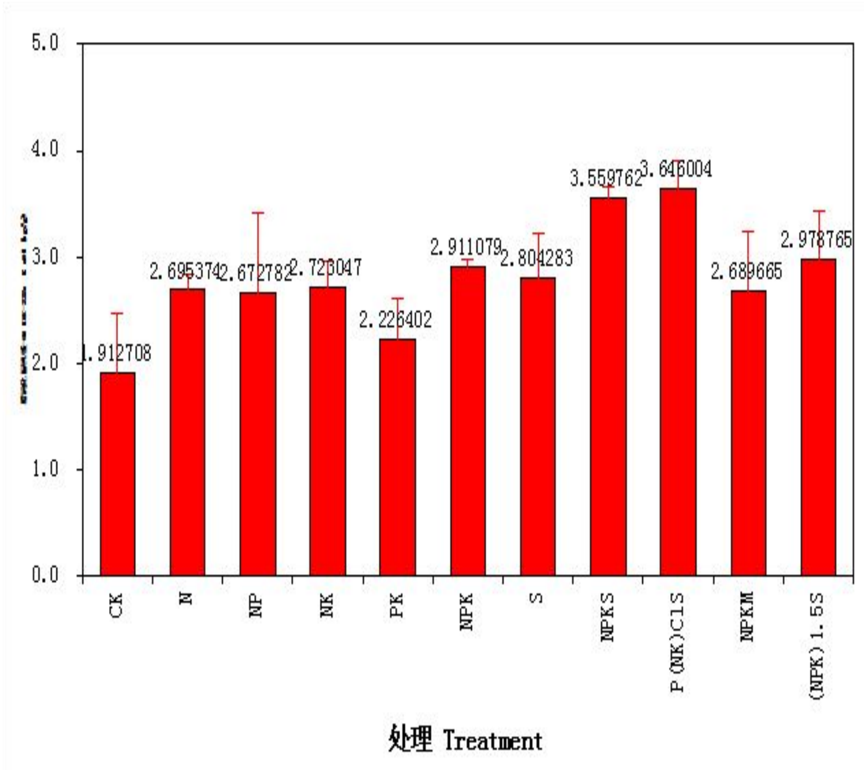
长期施肥对紫色土有机碳固定效率的影响

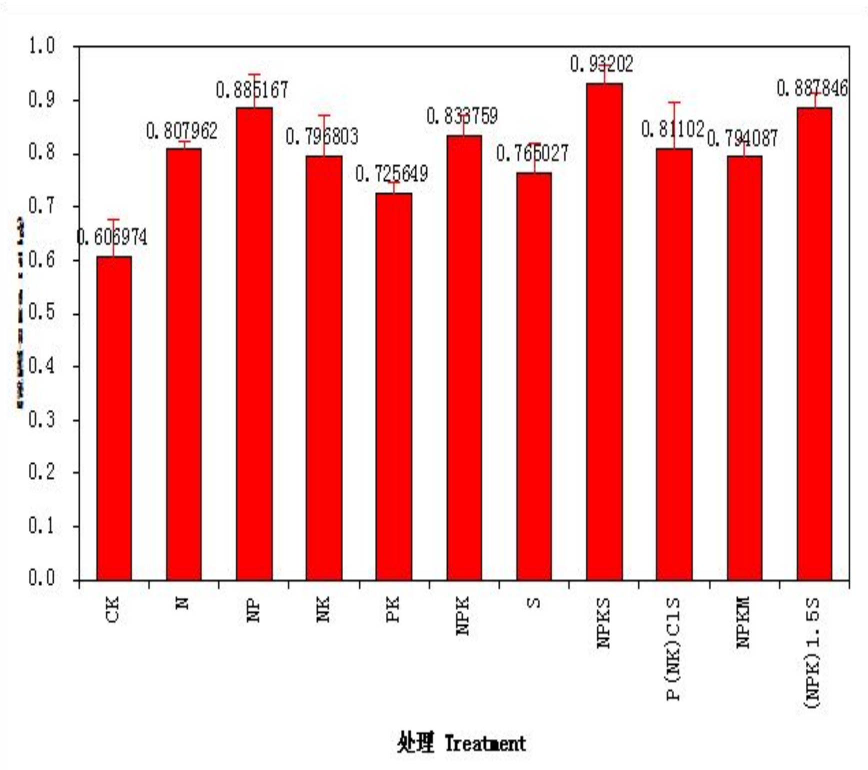
处理 Treatment	碳输入carbon input($t \cdot ha^{-1}$)							固碳效率 Efficiency (%)
	根茬stubble		根系root		有机肥 manure	秸秆 straw	总计 total	
	水稻 rice	小麦 wheat	水稻 rice	小麦 wheat				
CK	1.16	2.09	14.6	5.35	0.0	0.0	23.2	6.8
N	1.95	2.70	22.6	6.71	0.0	0.0	33.9	-1.7
NP	2.05	3.60	25.5	9.76	0.0	0.0	40.9	8.8
NK	2.27	2.70	26.3	6.70	0.0	0.0	38.0	3.7
PK	1.45	2.58	18.8	6.53	0.0	0.0	29.4	10.9
NPK	2.33	4.46	28.7	11.88	0.0	0.0	47.4	7.7
S	1.49	2.21	18.4	5.54	14.6	45.8	88.1	3.3
NPKS	2.51	4.47	30.6	11.97	0.0	59.3	108.9	4.1
$P(NK)_{Cl}S$	2.37	4.65	28.7	12.52	14.6	45.8	108.6	3.6
$(NPK)_{1.5}S$	2.56	5.11	29.3	13.04	14.6	45.8	110.4	6.6
NPKM	2.34	4.56	28.6	11.94	64.0	0.0	111.5	1.8

土壤有机碳与碳输入的关系



长期施肥对易氧化有机碳的影响

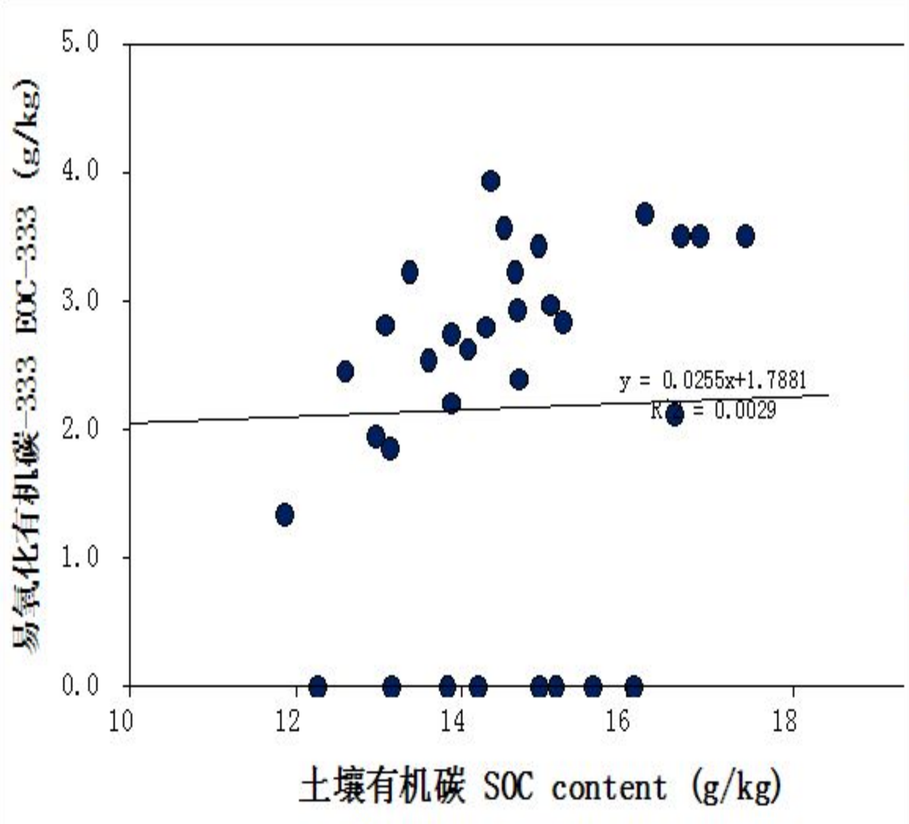


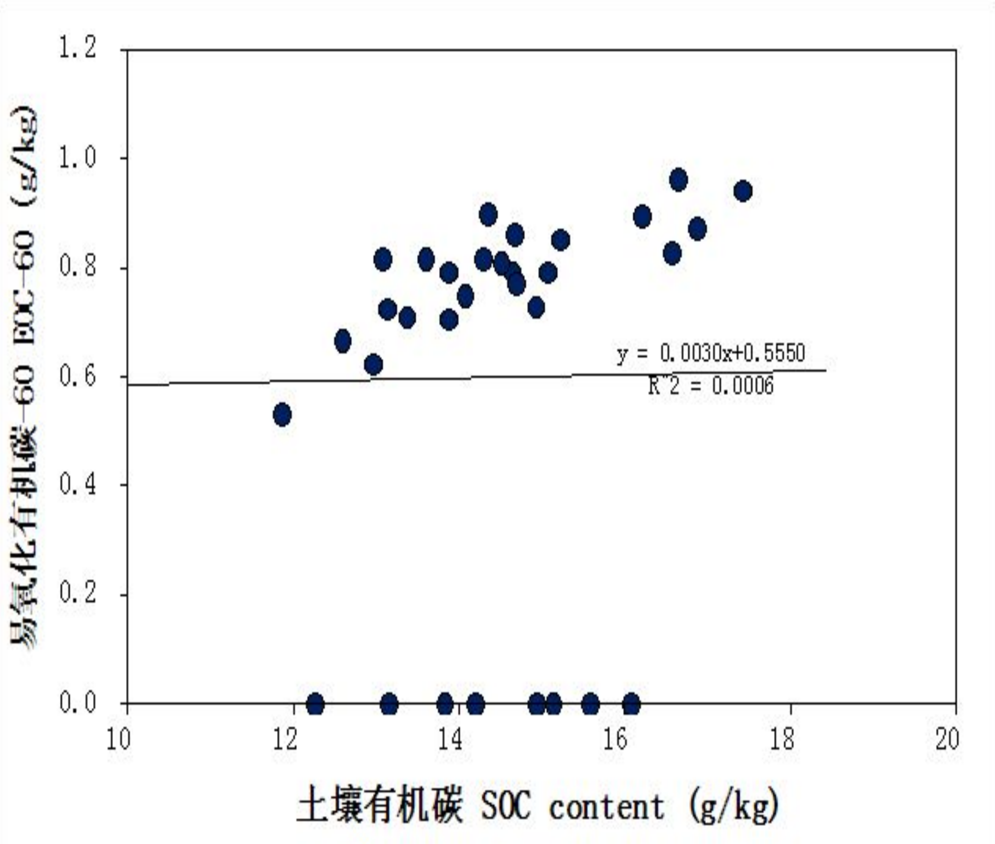


- 333mM高锰酸钾：含量1.91-3.65g/kg，占15.4%-24.8%；NPK>NK，N，NP>PK>CK
- 60mM高锰酸钾：0.61-0.93mg/kg，占4.9%-5.9%；NP>NPK>N，NK>PK>CK

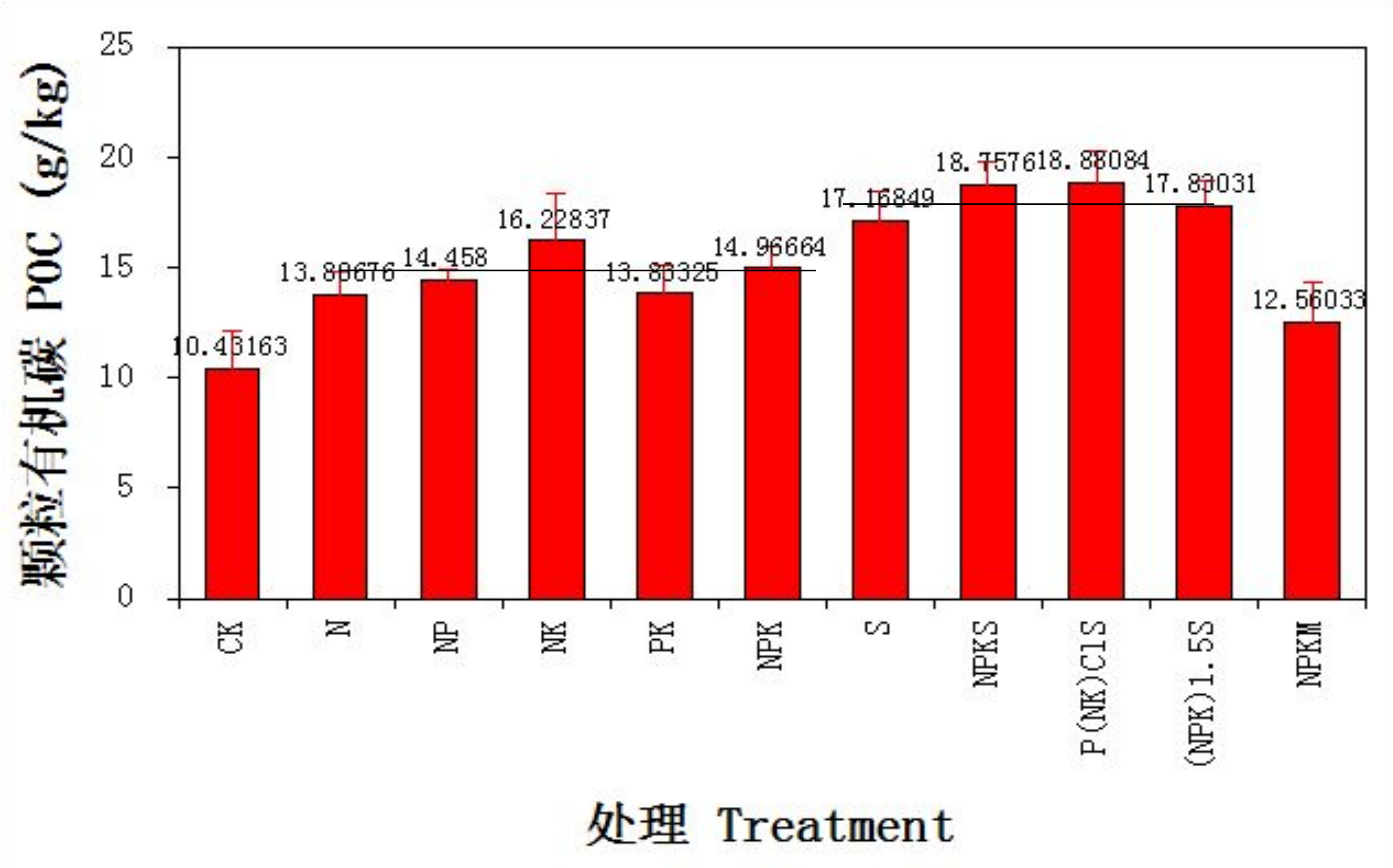
测定方法: Blair, 1995; Vieira et al.，2007

易氧化有机碳与全土有机碳的关系



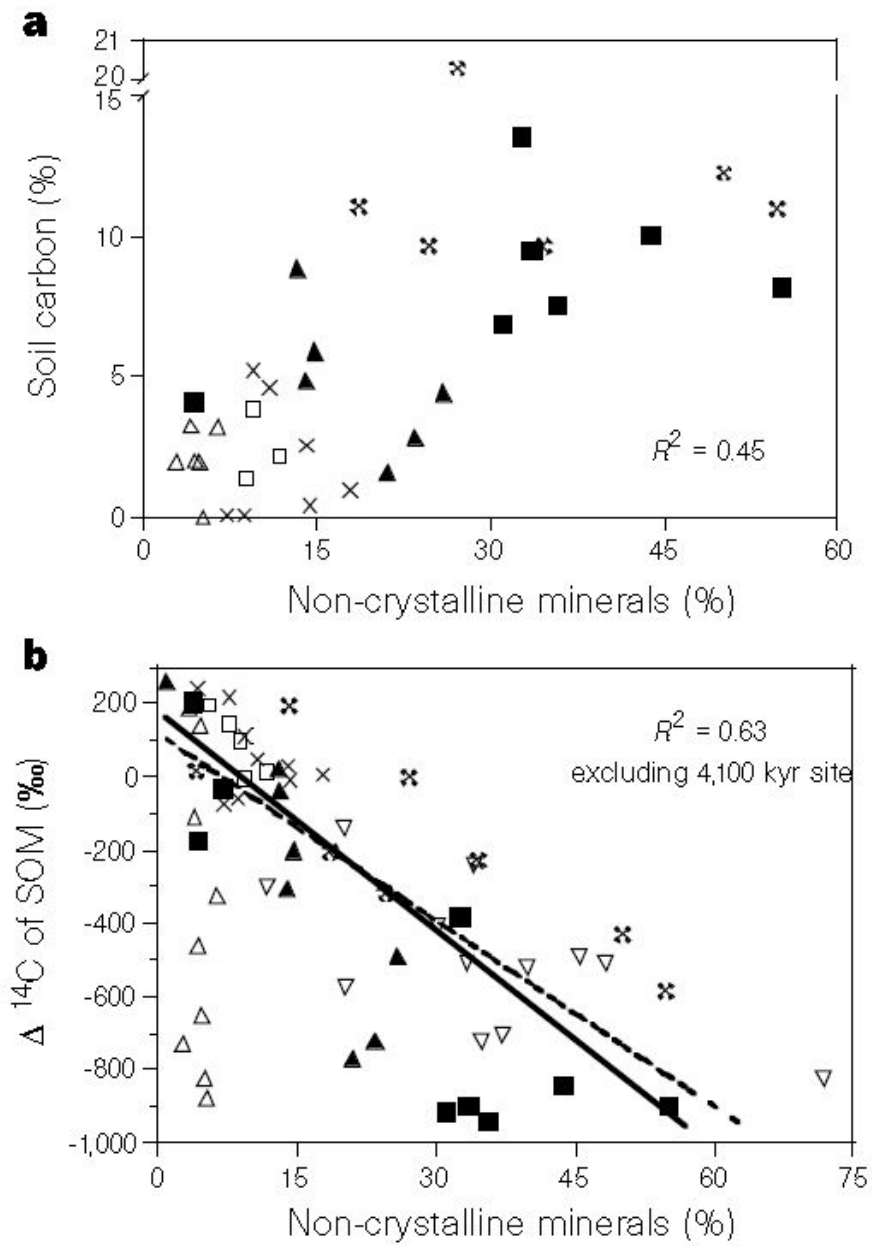


长期施肥对紫色土颗粒有机碳的影响



测定方法: Cambardella, 1992; Vieira et al.，2007

土壤有机碳与非晶型氧化物的关系



●非晶质矿物和有机碳间存在正相关性，有机质积累和损失是由矿质稳定性碳所决定（*Torn，1997，Nature*）

●Wiseman（2005，EJSS）分析德国中部6种土壤认为，铁铝氧化物决定了该地图土壤有机碳的稳定。火山灰土、氧化土、酸性土中，非晶形铁铝氧化物与有机碳之间的相互作用可能是最主要的稳定机制。

●Kleber酸性土壤底土层，非晶形铁铝氧化物通过配位体置换决定了土壤有机碳的稳定性。

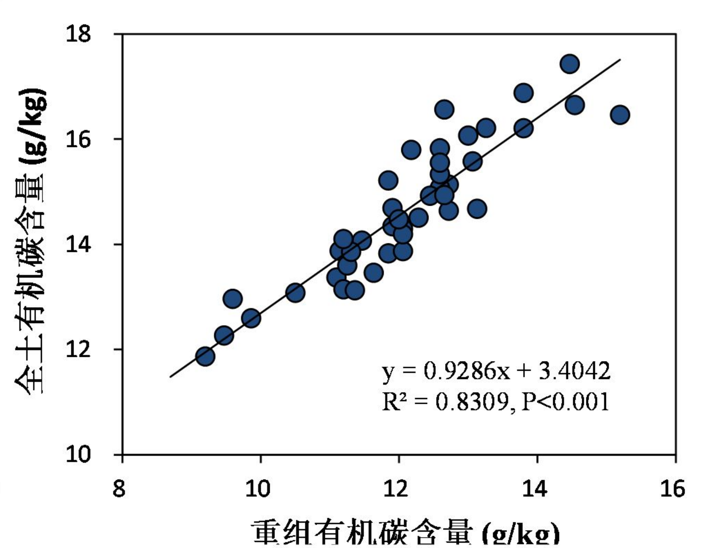
●在河海淀积物中，21.5%±8.6的有机碳与活性铁直接结合，其主要通过共沉降或直接的螯合作用而结合，进而使有机碳得到保护(Lalonde，2012，Nature) 。

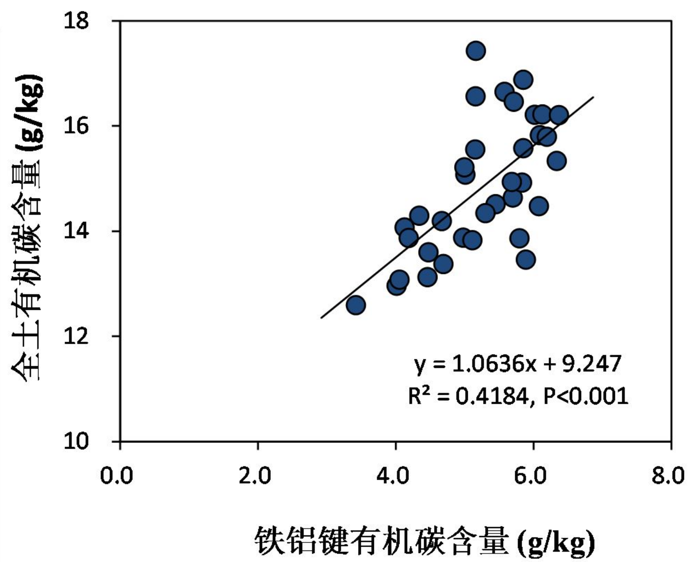
长期施肥对紫色土矿质有机碳的影响

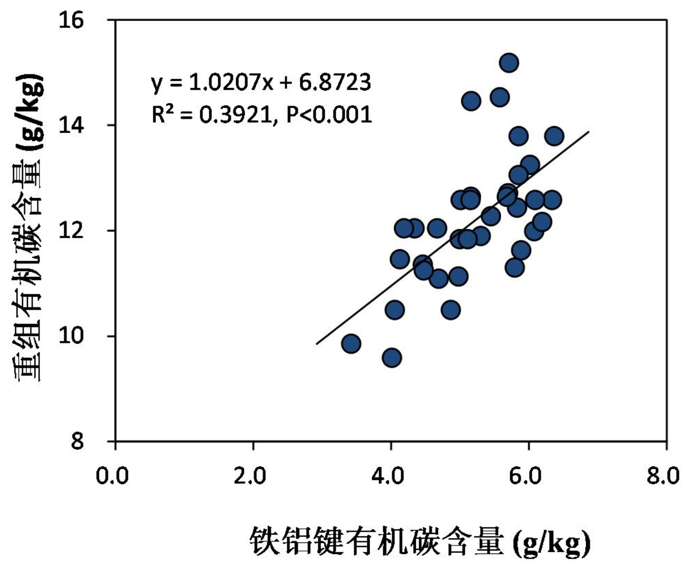
处理	重组有机碳 (g/kg)			钙镁键有机碳 (g/kg)			铁铝键有机碳 (g/kg)		
	M	SD	CV	M	SD	CV	M	SD	CV
CK	9.5	0.3	2.9	0.272	0.021	7.7	3.71	0.42	11.2
N	11.5	0.7	6.5	0.328	0.033	9.9	4.34	0.28	6.3
NP	12.1	0.7	5.4	0.257	0.009	3.6	5.81	0.57	9.9
NK	11.9	0.5	4.6	0.276	0.026	9.3	6.02	0.24	4.0
PK	11.5	0.3	2.6	0.264	0.017	6.5	4.66	0.46	9.8
NPK	12.6	0.6	4.6	0.292	0.026	9.0	5.00	0.01	0.2
S	11.6	0.5	4.2	0.263	0.020	7.5	4.51	0.25	5.5
NPKS	13.8	0.8	5.6	0.288	0.028	9.8	5.65	0.37	6.6
$P(NK)_{Cl}S$	12.3	0.3	2.6	0.320	0.014	4.3	5.56	0.24	4.3
$(NPK)_{1.5}S$	14.3	0.8	5.6	0.317	0.027	8.5	6.01	0.29	4.9
NPKM	12.1	1.1	9.0	0.292	0.030	10.4	5.24	0.42	8.0

测定方法: 鲁如坤，1999

矿质有机碳与全土有机碳的关系



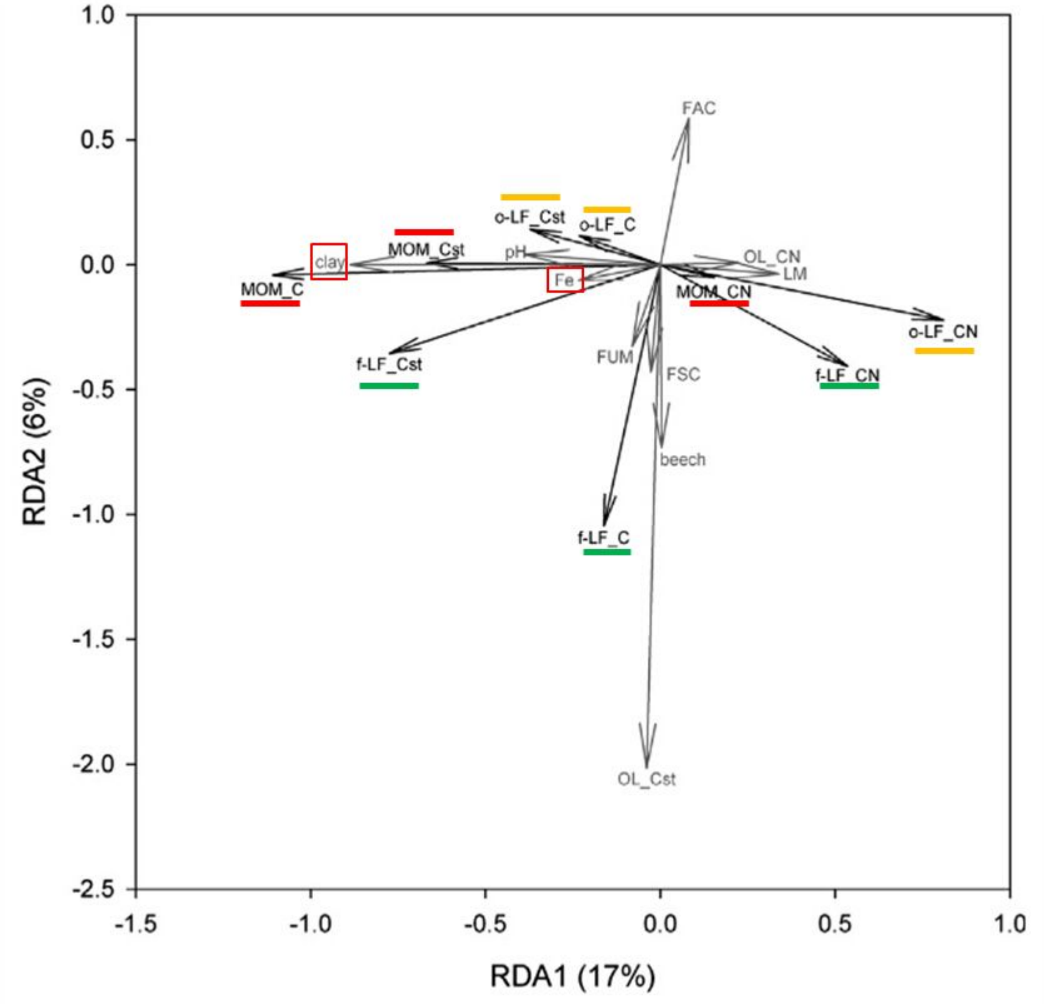




主要内容

- ➢研究背景
- ➢试验介绍
- ➢结果与分析
- ➢展望

多种稳定机制的综合作用



Gruneberg, 2013, Forest Ecology and Management

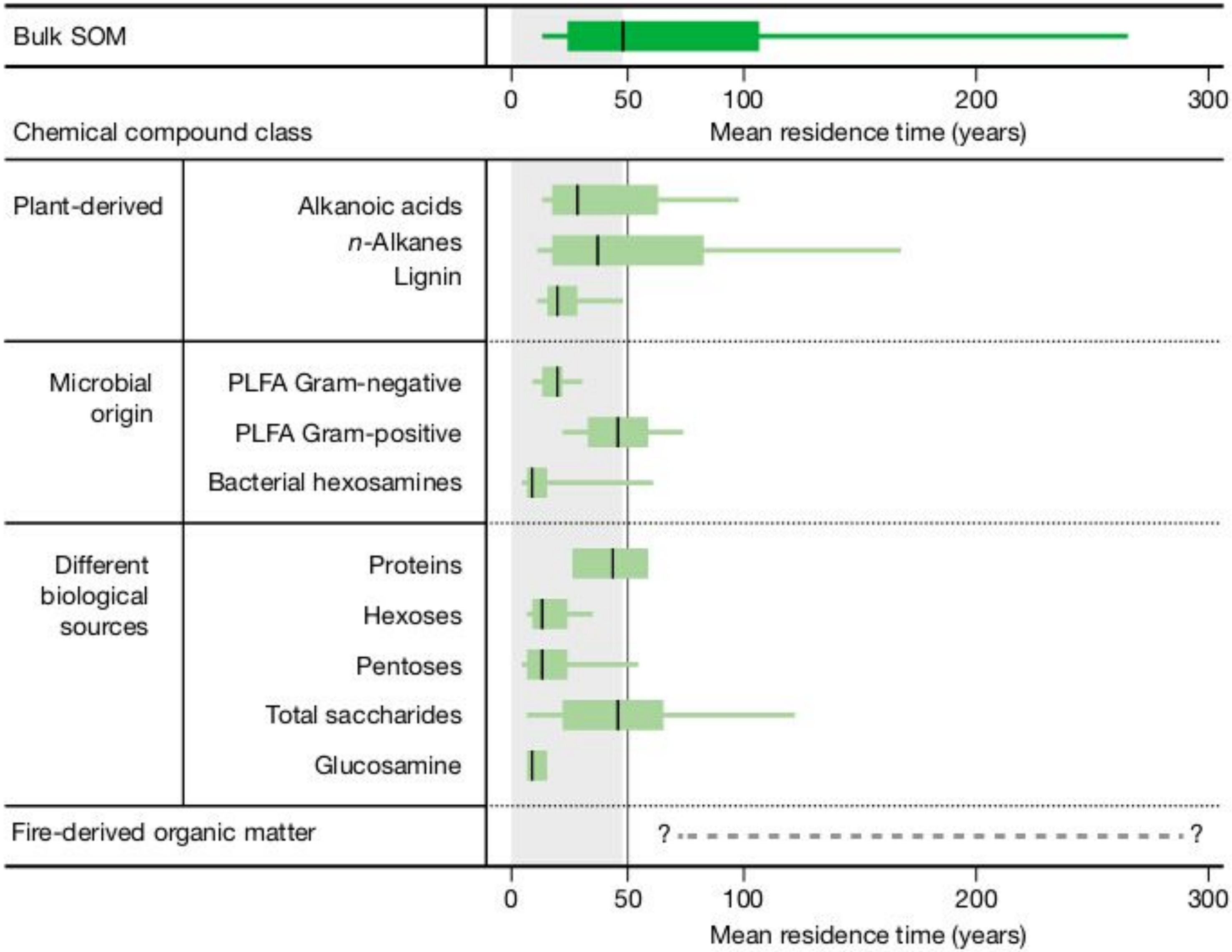
大团聚体内的微团聚体在土壤固碳中的作用

Table 1
Agricultural management effects on total soil organic C (TOC) and microaggregate-within-macroaggregate C (mM-C) stocks.

Soil type	Location	Soil classification	Texture/dominant clay mineralogy	Management change	Depth (cm)	Change in TOC ($g\ C\ m^{-2}$)	Contribution of mM-C (%)[b]	Reference
Mollisol	Sidney, NE (USA)	Pachic Haplustoll	Loam/2:1[a]	CT to NT	0–20	431 ± 14	91 ± 6	Denef et al. (2004)
Aridisol	Penaflor, Spain	Xerollic calciorthid	Loam/2:1	CT to NT	0–20	465 ± 49	49 ± 20	Alvaro-Fuentes et al. (2009)
Entisol/Alfisol	Davis, CA (USA)	Typic Xerothent/ Mollic Haploxeralf	Silt loam/Silty clay loam/2:1	RWC to RWL[c]	0–15	267 ± 12	108 ± 33	Kong et al. (2005)
	Davis, CA (USA)	Typic Xerothent/ Mollic Haploxeralf	Silt loam/2:1	RWL to OMT[c]	0–15	323 ± 24	61 ± 30	Kong et al. (2005)
	Davis, CA (USA)	Typic Xerothent/ Mollic Haploxeralf	Silt loam/2:1	CMT to OMT[c]	0–15	512 ± 24	NS	Kong et al. (2005)
Alfisol	Wooster, OH (USA)	Typic Fragiudalf	Silt loam/2:1	CT to NT	0–20	2050 ± 121	75 ± 4[c]	Six et al. (unpublished)
	Lexington, KY (USA)	Typic Paleudalf	Silt/mixed 2:1 & 1:1	CT to NT (0 N)	0–20	617 ± 95	81 ± 7	Chung et al. (2008)
				CT to NT (84 N)	0–20	607 ± 72	82 ± 9	Chung et al. (2008)
				CT to NT (84 N)	0–20	968 ± 104	93 ± 8	Denef et al. (2004)
				CT to NT (168 N)	0–20	678 ± 85	109 ± 13	Chung et al. (2008)
				CT to NT (336 N)	0–20	745 ± 179	112 ± 32	Chung et al. (2008)
	Lexington, KY (USA)	Typic Paleudalf	Silt/mixed 2:1 & 1:1	0 N to 168 N (CT only)	0–20	385 ± 53	NS	Chung et al. (2008)
	Lexington, KY (USA)	Typic Paleudalf	Silt/mixed 2:1 & 1:1	0 N to 168 N (NT only)	0–20	446 ± 85	49 ± 12[c]	Chung et al. (2008)
Ultisol	Horseshoe Bend, GA (USA)	Rhodic Kanhapludult	Sandy loam/1:1	CT to NT	0–20	578 ± 91	95 ± 12	Simpson et al. (2004)
Oxisol	Passo Fundo (Brazil)	Typic Haplorthox	Clay/1:1	CT to NT	0–20	382 ± 134	99 ± 9	Denef et al. (2004)

Six et al, 2014, SBB

土壤有机碳稳定性与分子结构的关系



Schmidt et al., 2011, Nature

土壤有机碳年龄与化学稳定性的关系

Global Change Biology

Global Change Biology (2011) 17, 1097–1107, doi: 10.1111/j.1365-2486.2010.02278.x

Old and stable soil organic matter is not necessarily chemically recalcitrant: implications for modeling concepts and temperature sensitivity

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谢谢