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自然降雨下蔬菜地土壤侵蚀及氮素流失特征

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摘要: 为探究自然降雨下露天蔬菜地土壤侵蚀及氮素养分流失特征, 基于径流小区原位观测试验, 设置叶菜类和果菜类这2种处理, 测定次降雨下不同类型蔬菜地坡面地表径流、侵蚀及其氮素(铵态氮和硝态氮)流失量, 探讨露天蔬菜种植坡面土壤侵蚀及氮素流失特征及影响因素。结果表明: ① 果菜类(茄子-辣椒)蔬菜地的地表径流、侵蚀量及铵态氮、硝态氮流失量显著高于叶菜类(油麦菜-红薯叶), 是后者的1.27~2.00倍。不同处理下第二季蔬菜坡面地表径流、侵蚀及其铵态氮和硝态氮流失占总流失量的50.86%~68.83%, 是第一季蔬菜的1.03~2.04倍。蔬菜地坡面地表径流、侵蚀及其氮素流失集中在6月和7月, 地表径流和侵蚀泥沙中氮素主要以地表径流中的硝态氮形式流失。② 次降雨下, 不同处理蔬菜地坡面地表径流、侵蚀及其养分流失在蔬菜生长期呈波动变化, 且流失量主要集中在几场典型降雨。整体上不同处理下第一季蔬菜地表径流和侵蚀泥沙中硝态氮和铵态氮流失量及含量低于第二季蔬菜, 果菜类地表径流、侵蚀量及铵态氮、硝态氮流失量高于叶菜类。③ 蔬菜地坡面地表径流、侵蚀及其铵态氮和硝态氮流失量与降雨量和最大30 min降雨强度等降雨参数呈极显著正相关关系。大雨降雨等级是引起蔬菜地土壤侵蚀及其铵态氮和硝态氮养分流失的主要降雨等级, 其次是暴雨和中雨, 分别贡献了29.58%~46.68%、24.54%~36.79%和24.01%~39.13%的流失量, 且不同蔬菜处理坡面地表径流、侵蚀与铵态氮和硝态氮流失对降雨等级的响应存在明显不同。研究结果有助于明晰南方露天蔬菜地土壤侵蚀及养分流失规律。

关键词: 蔬菜种植; 降雨; 土壤侵蚀; 铵态氮; 硝态氮

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Characteristics of Soil Erosion and Nitrogen Loss in Vegetable Field Under Natural Rainfall

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Abstract: The effects of vegetable planting on soil loss and nutrient loss, runoff, soil erosion, and nitrogen (ammonium nitrogen and nitrate nitrogen) losses under individual rainfalls of fruit- and leaf-vegetable fields between April to October in 2021 were observed using in-situ observation testing. The results showed that: ① the runoff, erosion, and nitrogen loss of the fruit-vegetable pattern (eggplant-chili) were 1.27-2.00 times those under the leaf-vegetable pattern (leaf lettuce-sweet potato leaves), especially under the second season vegetable period. Those losses under the second season vegetable accounted for 50.86%-68.83% of the total losses under different vegetable patterns, which were approximately 1.03-2.04 times those under the first season vegetable. The runoff, erosion, and nutrient loss of vegetable fields under different treatments were both concentrated in June and July, and the nitrogen loss was mainly in the form of nitrate nitrogen with surface runoff. ② The runoff, erosion, and nutrient losses under individual rainfalls of vegetable fields under different treatments fluctuated among the vegetable growing season, and the losses were mainly concentrated in several typical rainfall events. On the whole, the loss and concentration of nitrate and ammonium nitrogen in runoff and erosion sediment of vegetables in the first season were lower than those in the second season. The runoff, erosion, and loss of ammonium nitrogen and nitrate nitrogen of fruit-vegetable were higher than those of leaf-vegetable. ③ Both rainfall amount and maximum 30 min rainfall intensity had significantly positive effects on runoff, soil loss, and nitrogen loss. Runoff, erosion, and nutrient losses under different vegetable patterns were mainly generated by moderate rain, heavy rain, and heavy rainstorms, which accounted for 29.58%-46.68%, 24.54%-36.79%, and 24.01%-39.13% of the total losses, respectively. The results also showed that soil erosion and nutrient losses generated by different rainfall grades were obviously different for the fruit- and leaf-vegetable treatments. The results indicated that the vegetable pattern had significant impacts on soil loss and nutrient loss, and the leaf-vegetable pattern could reduce soil erosion and nutrient loss compared with the fruit-vegetable pattern. Furthermore, for different vegetable patterns and vegetable growing seasons, the effects of rainfall on soil loss and nutrient loss were quite different. The results of this study were helpful in clarifying the soil erosion and nutrient loss characteristics of vegetable fields in South China.

Key words: vegetable cultivation; rainfall; soil erosion; ammonium nitrogen; nitrate nitrogen

蔬菜是城乡居民生活必不可少的重要农产品, 其在我国农业生产结构占很大的比例, 仅次于粮食作物的第二大农作物, 全国蔬菜种植面积占农作物种植总面积的12.83%^[1]。而蔬菜化肥养分用量远高于其他农作物, 我国蔬菜化肥养分(N + P₂O₅ + K₂O)用量平均值为1 092.0 kg·hm⁻², 是全国农作物化肥养分用量(328.5 kg·hm⁻²)的3.3倍^[2]。有研究表明, 我国蔬菜地每年随径流流失的氮、磷养分高

达1.52 Tg和0.33 Tg^[3]。蔬菜种植区土壤氮磷养分积累明显, 显著高于其他作物^[4,5], 其土壤养分流失量也存在明显不同。例如, 陈安强等^[6]研究表明蔬菜地沟渠径流氮磷流失量要明显大于水稻田和苗木

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田,谢坤等^[7]研究4种植类型下农田径流中氮磷养分流失量表现为:蔬菜地>烟草>苗木>水稻.蔬菜地养分流失的研究一直以来集中在对设施菜地的氮磷养分流失,尤其是淋溶流失^[8-10].

近些年,随着国家推广“南菜北运”政策,南方露天蔬菜种植面积占比明显增大,例如,2020年广西蔬菜种植面积高达 $1\,535.9 \times 10^3 \text{ hm}^2$,占广西农作物种植总面积的25.2%^[11].蔬菜作物根系较浅,施肥量大、复种指数高^[12,13],蔬菜地土壤表层中氮、磷养分过多积累,肥料中的氮、磷等在降雨冲刷下易通过地表径流进入水体造成水体富营养化^[14,15].徐捷等^[16]研究指出,太湖流域甘蓝生长季氮素流失的主要途径是地表径流,其流失量高达 $19.66 \sim 38.03 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{Ma}$ 等^[17]基于模拟降雨试验指出,不同处理下蔬菜地中地表径流的溶解态氮流失量是壤中流中养分流失量的10.77~271.25倍不等.蔬菜地氮磷流失受降雨的年际分布^[18]、蔬菜生长季^[19,20]、蔬菜类型^[21,22]等因素的综合影响.雨季时期蔬菜地养分流失严重,降雨量和降雨强度是影响其养分流失的重要因素^[23].蔬菜种植期间跨越汛期(6~9月)种植时,坡面地表径流及其携带的氮磷养分流失量也较大^[24].Wang等^[3]研究结果表明,果菜类蔬菜地坡面径流中氮磷流失量要明显大于叶菜类等蔬菜类型.由于坡面氮磷养分流失机制的复杂性以及蔬菜类型、土壤条件等区域性,目前露天菜地坡面径流及养分流失特征主要

集中于太湖流域等地区^[25,26],对于广西等南方年降雨量大且集中度高的地区,次降雨下露天蔬菜地氮磷养分流失特征目前尚不清晰,高强度连续降雨下不同蔬菜类型坡面土壤侵蚀及养分流失特征也有待深入研究.

基于此,本文以赤红壤缓坡露天蔬菜地为研究对象,测定自然降雨下不同蔬菜类型坡面地表径流及侵蚀泥沙流失量及其氮素养分流失量,获得降雨特征和蔬菜类型对蔬菜地坡面土壤侵蚀及氮素养分流失特征,探讨降雨特征及蔬菜类型对蔬菜地土壤侵蚀及氮素流失的影响机制,研究结果对于明晰蔬菜地中氮磷的流失特征及减少农田面源污染具有重要现实意义,同时也可作为区域农业种植结构规划提供理论依据.

1 材料与方 法

1.1 研究区概况

研究区位于广西壮族自治区南宁市,试验地点位于广西大学校内农科试验基地($E108^{\circ}17'38''$, $N22^{\circ}50'59''$).该地区属亚热带季风气候,年平均气温为 22°C ,年均相对湿度为79%,年均降雨量在1300 mm左右,其中5~9月降雨量占全年降雨量的70%左右.两种蔬菜种植类型的土壤属性一致,土壤类型为赤红壤,土壤母质为第四纪红黏土,质地为黏壤土,耕层深度为40 cm,容重为 $1.27 \text{ g} \cdot \text{cm}^{-3}$,其他基本理化性质见表1.

表1 试验土壤基本理化性质

Table 1 Chemical and physical properties of experimental soil

项目	pH	ω (有机质) / $\text{g} \cdot \text{kg}^{-1}$	ω (全氮) / $\text{g} \cdot \text{kg}^{-1}$	ω (硝态氮) / $\text{mg} \cdot \text{kg}^{-1}$	ω (铵态氮) / $\text{mg} \cdot \text{kg}^{-1}$	ω (全磷) / $\text{g} \cdot \text{kg}^{-1}$	土壤颗粒组成/%		
							砂粒	粉粒	黏粒
参数	6.70	6.78	1.13	8.57	12.37	0.59	45.2	30.2	24.6

1.2 试验设计

本试验采取径流小区野外原位观测法,坡度为 3° ,坡长为3 m,宽度1.5 m.小区底部修建出水口,出水口下方安装有体积200 L的集流槽,用于收集降雨过程中小区坡面径流泥沙样.观测时间为2021年4~10月,包括两季露地蔬菜,设置叶菜类和果菜类2种蔬菜处理,每处理设1次重复.叶菜类一年两季蔬菜分别为油麦菜(品种为四季香妃)和红薯叶(品种为福薯18号),果菜类一年两季蔬菜为茄子(品种为紫

红长茄)和辣椒(品种为辣丰三号),第一季蔬菜于4月28日移栽,6月30日收获,第二季蔬菜于7月7日移栽,10月5日收获.不同处理施肥均以化学氮肥为尿素(N 46%)、磷肥为过磷酸钙(P_2O_5 16%)、钾肥为硫酸钾(K_2O 50%)和有机肥(N 2.2%, P_2O_5 1.36%, K_2O 1.96%)配合施用,其中有机肥施用量均为 $5\,000 \text{ kg} \cdot \text{hm}^{-2}$,有机肥和磷肥作为基肥在每季作物种植时一次性施入,氮肥和钾肥按30%基肥和70%追肥分次施入.具体试验及施肥处理见表2.

表2 试验田间管理与施肥方案

Table 2 Pilot field management and fertilization program

处理	第一季-第二季	种植规格(株行距) / cm	施肥量($\text{N-P}_2\text{O}_5\text{-K}_2\text{O}$) / $\text{kg} \cdot \text{hm}^{-2}$	施肥时间(月-日)	
				基肥	追肥
叶菜类	油麦菜-红薯叶	20×20	420-200-300	04-25	05-25, 06-05, 06-11
果菜类	茄子-辣椒	40×40	550-220-300	07-05	08-01, 08-11, 08-25

1.3 样品采集与分析

每次降雨产生径流后,利用标尺测定径流池水深,将径流池内径流与泥沙充分搅匀后,用 500 mL 塑料瓶取坡面径流泥沙样,每个小区取 3 瓶.静置样品,待样品充分沉淀后,滤除上清液,径流样置于 4℃ 冰箱保存,并在 48 h 内测定,泥沙样通过风干或低温烘干(45℃)后称重并收集备用,参照文献[27]按次降雨下计算径流含沙浓度、坡面径流量、坡面侵蚀量等参数.测定指标包括径流水样和泥沙样中铵态氮($\text{NH}_4^+ - \text{N}$)和硝态氮($\text{NO}_3^- - \text{N}$),实验室所测径流的浓度减去降雨雨水中平均养分浓度(铵态氮: $0.08 \text{ mg} \cdot \text{L}^{-1}$,硝态氮: $0.64 \text{ mg} \cdot \text{L}^{-1}$)即为径流中相应养分浓度.径流水样和雨水水样中铵态氮($\text{NH}_4^+ - \text{N}$)和硝态氮($\text{NO}_3^- - \text{N}$)经 $0.45 \mu\text{m}$ 滤膜进行抽滤后用连续流动化学分析仪(型号:AA3,产地:德国)测定,泥沙中铵态氮($\text{NH}_4^+ - \text{N}$)和硝态氮($\text{NO}_3^- - \text{N}$)经 $2 \text{ mol} \cdot \text{L}^{-1}$ 的 KCl 溶液提取后,用连续流动化学分析仪(型号:AA3,产地:德国)测定.

试验期内降雨数据由试验区附近气象站自记式雨量计获得,统计得到降雨量、降雨历时、平均雨强和最大 15 min、30 min 降雨强度(I_{15} 、 I_{30})等降雨特征参数.2021 年 4 ~ 10 月总降雨量为 1 267 mm,总降雨天数为 107 d,具体降雨分布见图 1.

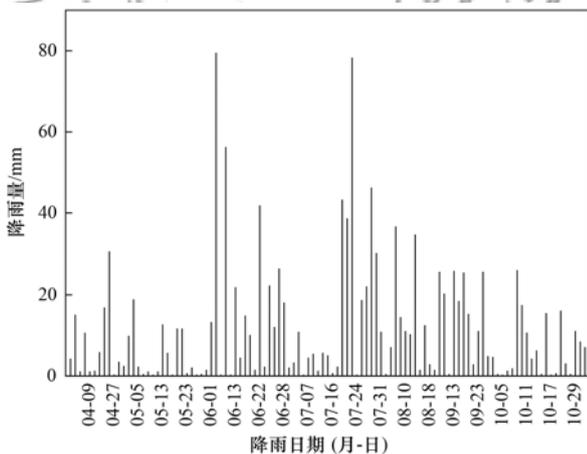


图 1 2021 年 4 ~ 10 月研究区降雨分布

Fig. 1 Rainfall distribution of the study area from April to October in 2021

1.4 数据处理

使用 Excel 2010 和 SPSS 25.0 统计分析软件进行数据处理;利用 Origin 2018 进行图表绘制.

2 结果与分析

2.1 蔬菜地坡面地表径流、侵蚀及氮素养分流失特征

2021 年 4 ~ 10 月蔬菜地坡面地表径流、侵蚀及其铵态氮、硝态氮流失量见表 3.对坡面径流和养分

流失而言,叶菜类处理下第一季(油麦菜)和第二季(红薯叶)蔬菜中氮素流失均以硝态氮为主,分别占每季坡面径流中氮素总流失量的 90.77% 和 88.34%,是各季铵态氮流失量的 9.84 和 7.57 倍.叶菜类处理下第二季蔬菜地表径流量、铵态氮、硝态氮流失量分别占其流失总量的 61.35%、65.95% 和 59.85%,是第一季蔬菜的 1.59、1.94 和 1.49 倍(表 3).果菜类处理下坡面径流中养分流失也以硝态氮为主(>89%),其中第二季(辣椒)蔬菜坡面径流量及其铵态氮、硝态氮量分别占 66.20%、68.83% 和 67.91%,分别是第一季(茄子)蔬菜的 1.96、2.21 和 2.12 倍.不同处理下,果菜类坡面径流量、铵态氮和硝态氮流失总量是叶菜类的 1.27、1.57 和 1.63 倍.二者差异主要集中在第二季蔬菜,果菜类第二季蔬菜坡面径流量、铵态氮和硝态氮流失量分别比叶菜类增加了 36.97%、63.78% 和 84.90%.结果表明,蔬菜地坡面地表径流中氮素流失均以硝态氮为主(>88%),且不同种植季间的养分流失存在显著不同,铵态氮和硝态氮流失均主要集中在第二季.

对于坡面侵蚀流失和养分流失而言,叶菜类和果菜类处理下第一季、第二季蔬菜侵蚀泥沙中氮素流失均以铵态氮为主,分别占每季蔬菜侵蚀泥沙中氮素流失总量的 78.71%、76.71% 和 78.49%、73.70%(表 3).叶菜类和果菜类处理下,第二季蔬菜坡面侵蚀量、铵态氮、硝态氮流失量分别占各流失总量的 54.41%、50.86%、53.73% 和 60.43%、61.83%、67.51%,是第一季蔬菜的 1.19、1.03、1.16 倍和 1.53、1.60、2.04 倍.果菜类处理下坡面侵蚀量、铵态氮和硝态氮流失量均显著高于叶菜类处理,是后者的 1.50、1.78 和 2.00 倍.果菜类处理下第一季蔬菜坡面侵蚀、铵态氮和硝态氮流失量分别比叶菜类处理增加了 30.33%、40.31% 和 43.24%,第二季则分别增加了 66.78%、116.29% 和 151.52%.综上所述,蔬菜地侵蚀泥沙中氮素流失形态以铵态氮为主;不同处理下,果菜类处理坡面侵蚀及氮素养分流失量显著高于叶菜类,且二者之间在第二季的差异更为明显.此外,由表 3 还可知,降雨条件下叶菜类和果菜类蔬菜随径流流失的铵态氮和硝态氮养分是泥沙流失的 10.17 ~ 11.46 倍,其中硝态氮是主要的流失形态(>88%).叶菜类处理坡面径流、侵蚀泥沙中铵态氮和硝态氮流失量显著低于果菜类处理.

2.2 次降雨下蔬菜地坡面地表径流、侵蚀及氮素流失特征

2.2.1 蔬菜地坡面地表径流及氮素流失特征

叶菜类和果菜类处理在 2021 年 4 ~ 10 月分别

表 3 不同处理坡面地表径流、侵蚀和氮素流失总量¹⁾

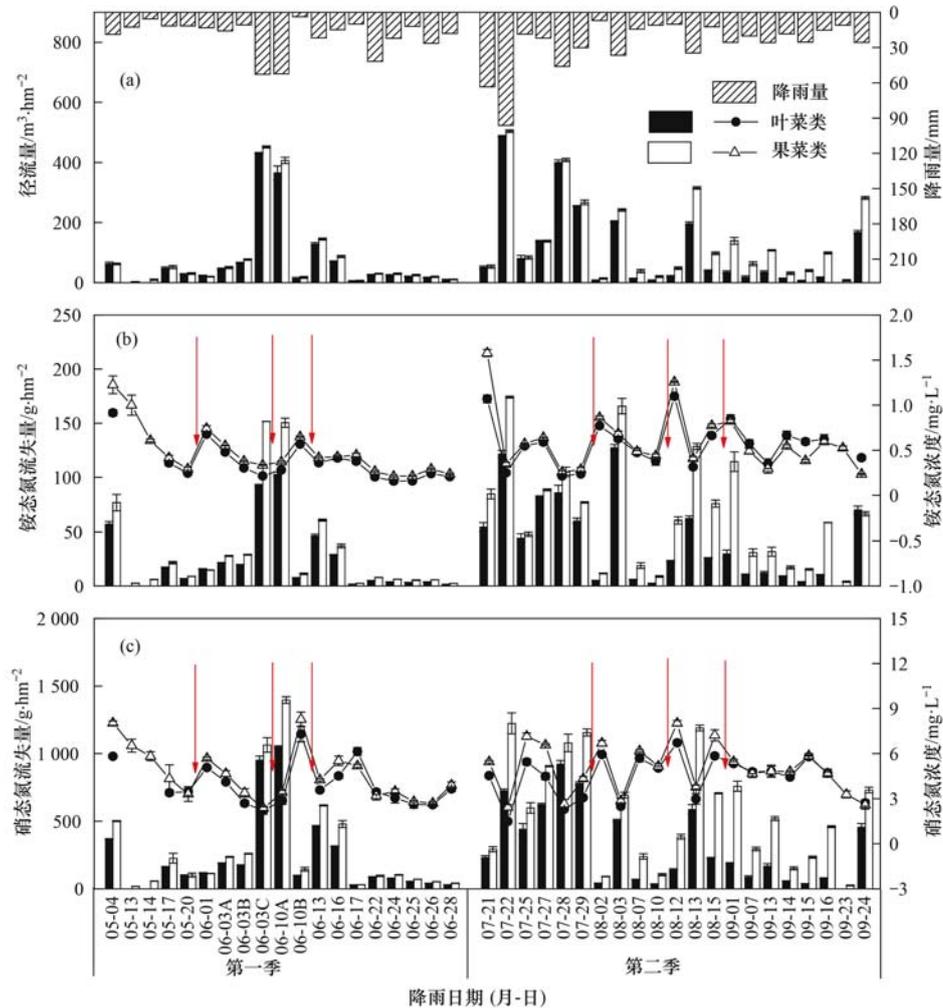
Table 3 Total amount of surface runoff, erosion, and nitrogen loss in different treatments

流失方式	指标	处理	第一季	第二季	总流失量
径流	径流量/ $\text{m}^3 \cdot \text{hm}^{-2}$	叶菜类	1 380.0 \pm 16.15b	2 190.6 \pm 17.89b	3 570.7 \pm 1.74b
		果菜类	1 532.1 \pm 2.98a	3 000.5 \pm 3.59a	4 532.5 \pm 6.57a
	铵态氮/ $\text{g} \cdot \text{hm}^{-2}$	叶菜类	436.5 \pm 4.20b	845.4 \pm 9.61b	1 281.9 \pm 5.41b
		果菜类	627.0 \pm 7.04a	1 384.6 \pm 2.65a	2 011.7 \pm 4.39a
	硝态氮/ $\text{g} \cdot \text{hm}^{-2}$	叶菜类	4 295.0 \pm 9.84b	6 402.3 \pm 55.51b	10 697.4 \pm 65.35b
		果菜类	5 593.1 \pm 11.18a	11 837.7 \pm 27.88a	17 430.9 \pm 39.05a
侵蚀	侵蚀量/ $\text{kg} \cdot \text{hm}^{-2}$	叶菜类	29 811.8 \pm 21.82b	35 584.1 \pm 267.66b	65 396.0 \pm 245.84b
		果菜类	38 855.2 \pm 23.82a	59 346.0 \pm 578.46a	98 201.2 \pm 602.27a
	铵态氮/ $\text{g} \cdot \text{hm}^{-2}$	叶菜类	399.2 \pm 26.14b	413.1 \pm 6.20b	812.3 \pm 19.93b
		果菜类	560.1 \pm 1.98a	893.5 \pm 47.28a	1 445.0 \pm 49.26a
	硝态氮/ $\text{g} \cdot \text{hm}^{-2}$	叶菜类	108.0 \pm 3.60b	125.4 \pm 4.40b	233.4 \pm 8.00b
		果菜类	154.7 \pm 3.05a	315.4 \pm 18.81a	467.2 \pm 21.85a

1) 数据为平均值 \pm 标准误差; 同列不同字母表示处理在 5% 水平上差异显著

有 37 场和 40 场侵蚀性降雨. 由图 2(a) 可知, 次降雨下叶菜类和果菜类坡面地表径流量在 $4.6 \sim 486.6 \text{ m}^3 \cdot \text{hm}^{-2}$ 和 $2.6 \sim 504.4 \text{ m}^3 \cdot \text{hm}^{-2}$ 之间, 除个别场次超过 $200 \text{ m}^3 \cdot \text{hm}^{-2}$ 外, 80% 左右的次降雨下均小于 $100 \text{ m}^3 \cdot \text{hm}^{-2}$, 且整体上第二季地表径流量

大于第一季. 次降雨下叶菜类和果菜类处理下铵态氮流失量介于 $1.7 \sim 127.4 \text{ g} \cdot \text{hm}^{-2}$ 和 $2.4 \sim 174.1 \text{ g} \cdot \text{hm}^{-2}$, 铵态氮浓度在 $0.2 \sim 1.1 \text{ mg} \cdot \text{L}^{-1}$ 和 $0.2 \sim 1.6 \text{ mg} \cdot \text{L}^{-1}$ 内波动变化[图 2(b)], 主要发生在 6 月和 7 月, 其中第一季 ($1.7 \sim 151.6 \text{ g} \cdot \text{hm}^{-2}$) 整体小于



A、B 和 C 分别表示同一日期内第一场、第二场和第三场降雨; 箭头表示施肥时间, 下同

图 2 次降雨下不同处理坡面径流量及其铵态氮、硝态氮流失特征

Fig. 2 Characteristics of slope runoff, ammonium nitrogen, and nitrate nitrogen loss under individual rainfalls of different treatments

第二季(2.5 ~ 174.1 g·hm⁻²). 次降雨下叶菜类和果菜类处理下硝态氮流失量在 28.4 ~ 1 049.5 g·hm⁻²和 29.6 ~ 1 396.2 g·hm⁻²,硝态氮浓度变化范围为 1.5 ~ 7.3 mg·L⁻¹和 2.6 ~ 8.2 mg·L⁻¹ [图 2 (c)], 波动较大, 其中次降雨流失量大于 500 g·hm⁻²的场次主要集中在第二季蔬菜. 次降雨下, 除 05-04、06-01 和 07-27 降雨外, 果菜类处理坡面地表径流量、铵态氮流失量和硝态氮流失量均大于叶菜类处理, 分别是叶菜类的 1.05 ~ 5.99、1.08 ~ 5.65 和 1.04 ~ 6.06 倍不等, 二者的差异在第二季蔬菜生长期(8 ~ 9 月) 尤为明显.

2.2.2 蔬菜地坡面侵蚀及氮素养分流失特征

由图 3(a)可知, 叶菜类和果菜类处理坡面侵蚀量在 43.0 ~ 9 541.8 kg·hm⁻² 和 76.5 ~ 11 596.2 kg·hm⁻²之间, 侵蚀量超过6 000 kg·hm⁻²的降雨在 6 月和 7 月, 第二季蔬菜的坡面侵蚀量整体上大于第

一季. 叶菜类和果菜类处理侵蚀泥沙中铵态氮流失量介于 0.3 ~ 120.5 g·hm⁻²和 1.5 ~ 162.8 g·hm⁻², 铵态氮含量在 7.1 ~ 32.1 mg·kg⁻¹ 和 6.5 ~ 35.0 mg·kg⁻¹间波动, 其中第二季蔬菜波动程度大于第一季[图 3(b)]. 叶菜类处理下硝态氮流失量和含量介于 0.1 ~ 32.7 g·hm⁻²和 1.5 ~ 12.9 mg·kg⁻¹, 而果菜类处理下介于 0.4 ~ 62.9 g·hm⁻²和 2.7 ~ 15.5 mg·kg⁻¹ [图 3(c)], 除个别场次硝态氮流失量超过 20 g·hm⁻²外, 其余降雨下整体上在 10 g·hm⁻²以下, 次降雨下不同处理第一季蔬菜地硝态氮流失量和硝态氮含量波动程度均小于第二季. 次降雨下, 除 05-04、05-17、06-01、07-22 和 07-27 这 5 次降雨外, 果菜类处理坡面侵蚀、泥沙中铵态氮和硝态氮流失量均大于叶菜类, 分别是叶菜类的 1.01 ~ 23.31、1.03 ~ 12.99 和 1.11 ~ 38.97 倍, 二者在第二季蔬菜差异最为明显.

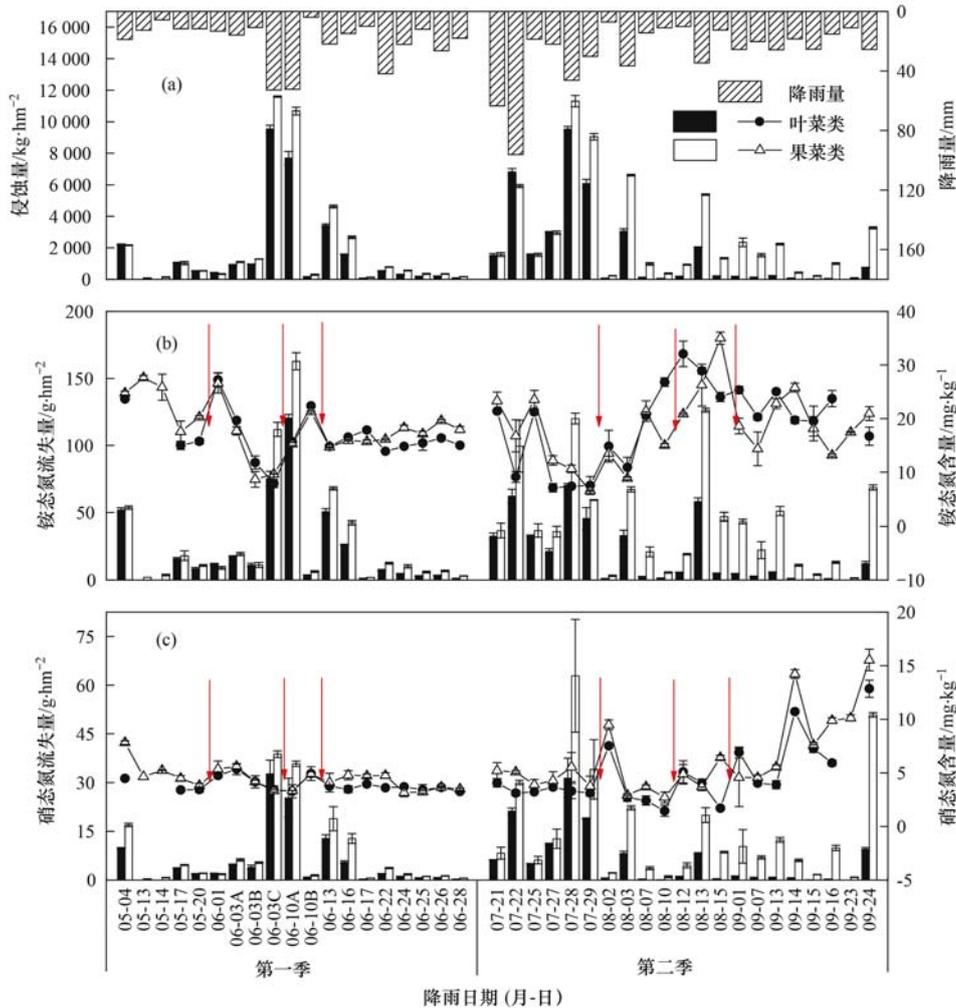


图 3 次降雨下不同处理坡面侵蚀量及其铵态氮、硝态氮流失特征

Fig. 3 Characteristics of slope erosion, ammonium nitrogen, and nitrate nitrogen loss under individual rainfalls of different treatments

2.3 降雨对蔬菜地土壤侵蚀及氮素养分流失的影响
对坡面径流、侵蚀及氮素养分与降雨特征参数进行相关分析可知(表 4). 不同处理下坡面径流侵

蚀及其铵态氮和硝态氮流失量均与降雨量、I₁₅ 和 I₃₀ 表现为极显著正相关关系, 且降雨量是影响坡面径流侵蚀和养分流失的最主要因子.

表 4 坡面径流、侵蚀及养分与降雨特征参数相关分析¹⁾

Table 4 Correlation analysis of slope runoff, erosion, and nutrients with rainfall characteristic parameters

处理	指标	降雨量	降雨历时	平均雨强	I_{15}	I_{30}
叶菜类	径流量	0.772 **	0.305	0.244	0.559 **	0.601 **
	径流铵态氮	0.715 **	0.236	0.320	0.503 **	0.573 **
	径流硝态氮	0.632 **	0.142	0.342 *	0.650 **	0.677 **
	侵蚀量	0.681 **	0.245	0.269	0.633 **	0.658 **
	泥沙铵态氮	0.650 **	0.168	0.388 *	0.697 **	0.684 **
	泥沙硝态氮	0.667 **	0.235	0.259	0.632 **	0.651 **
果菜类	径流量	0.763 **	0.254	0.291	0.600 **	0.638 **
	径流铵态氮	0.731 **	0.225	0.359 *	0.563 **	0.613 **
	径流硝态氮	0.636 **	0.119	0.385 *	0.608 **	0.636 **
	侵蚀量	0.635 **	0.096	0.397 *	0.754 **	0.780 **
	泥沙铵态氮	0.677 **	0.119	0.401 *	0.713 **	0.720 **
	泥沙硝态氮	0.582 **	0.076	0.326 *	0.594 **	0.638 **

1) * 表示显著相关 ($P < 0.05$); ** 表示极显著相关 ($P < 0.01$)

为进一步分析降雨量对坡面径流、侵蚀及氮素流失的影响,将观测期内侵蚀性降雨按照中国气象降雨等级^[28]划分为小雨、中雨、大雨和暴雨4个降雨等级(表5)。2021年4~10月侵蚀性降雨总量为

946.0 mm,占总降雨的74.66%,侵蚀性降雨中中雨降雨等级发生的频次和降雨量占比均最高,其次是大雨和暴雨降雨等级。

由图4可知,叶菜类处理下坡面地表径流量、

表 5 2021年4~10月研究区侵蚀性降雨特征

Table 5 Characteristics of erosive rainfall in the study area from April to October 2021

降雨等级	降雨历时/h	降雨量/mm	平均雨强/ $\text{mm}\cdot\text{h}^{-1}$	I_{30} / $\text{mm}\cdot\text{h}^{-1}$	降雨场次/场	总降雨量/mm	占侵蚀性降雨总量比例/%
小雨	0.4~5.8	3.8~7.0	1.3~14.0	6.8~13.6	3	16.4	1.7
中雨	0.3~10.7	10.0~22.2	1.2~35.2	8.4~37.2	23	346.6	36.6
大雨	0.8~10.6	25.4~46.2	0.9~31.0	14.0~76.8	10	318.7	33.7
暴雨	1.6~22.3	52.4~96.2	3.1~32.1	17.2~88.4	4	264.8	28.0

铵态氮和硝态氮流失量均主要来源于大雨降雨等级,占总流失量的37.53%、35.86%和35.22%;其次是暴雨(27.63%~37.36%)和中雨(24.54%~35.74%)降雨等级。果菜类处理下大雨和中雨降雨等级则分别贡献了40.84%、35.61%、38.19%和27.01%、35.07%、37.30%的坡面地表径流、铵态氮和硝态氮流失。不同降雨等级下,果菜类处理坡面径流、铵态氮和硝态氮流失量均显著高于叶菜类处理。对不同降雨等级下坡面侵蚀量和氮素流失量而言(图4),叶菜类处理下坡面侵蚀量、泥沙铵态氮和硝态氮流失量主要来源于暴雨(39.13%、35.77%和36.64%),其次是大雨(34.46%、29.58%和34.70%)和中雨(26.03%、34.04%和28.06%)。果菜类处理下大雨等级产生的坡面侵蚀量、铵态氮和硝态氮流失量占比最高(42.30%、38.47%和46.68%)。不同处理下坡面地表径流、侵蚀及其养分流失对降雨等级响应存在明显不同。叶菜类处理下,中雨、大雨和暴雨降雨等级对坡面径流、侵蚀及养分流失贡献接近(30%左右);而果菜类处理下坡面径流量和侵蚀量均主要来源于大雨降雨等级(>40%),径流、侵蚀泥沙中铵态氮和硝态

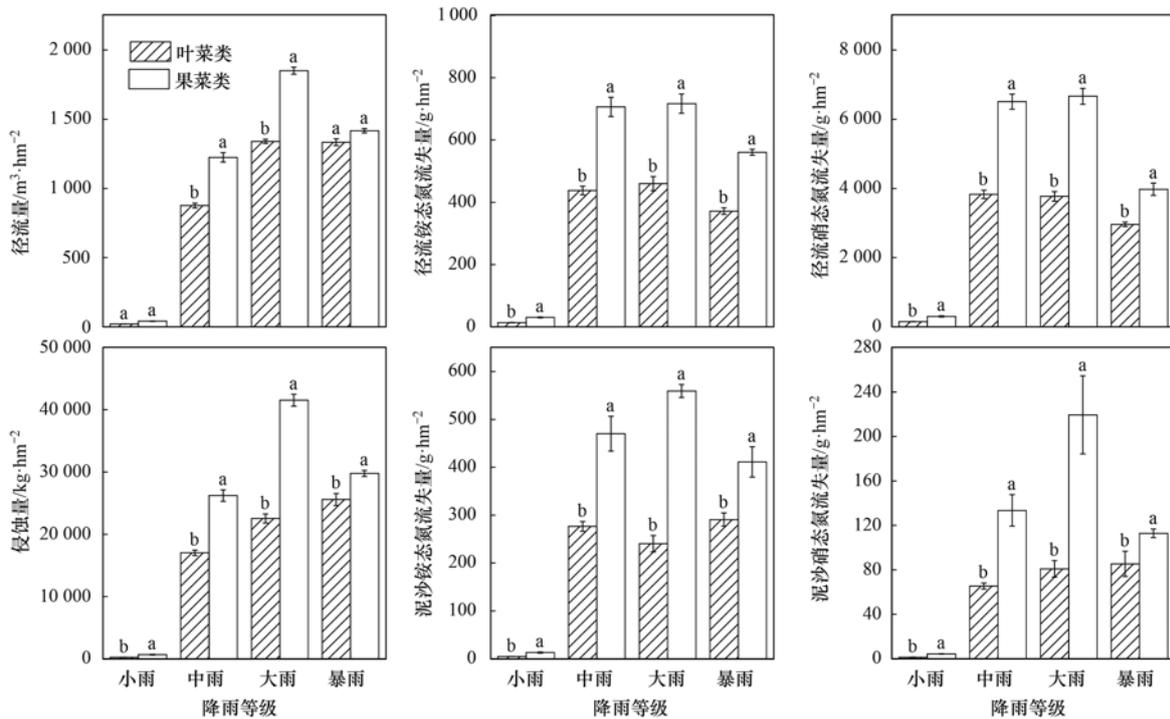
氮流失量主要由中雨(28.38%~37.30%)和大雨(35.61%~46.68%)降雨等级贡献。

3 讨论

3.1 蔬菜种植对坡面土壤侵蚀及氮素流失的影响

对比蔬菜地地表径流和侵蚀泥沙中铵态氮和硝态氮流失量可知,地表径流中铵态氮和硝态氮流失量远大于其随侵蚀泥沙的流失量,同时地表径流中以硝态氮流失为主,侵蚀泥沙中铵态氮流失为主。Ma等^[17]研究指出,地表径流中硝态氮流失量占径流中溶解态氮流失量的95%以上。坡面侵蚀泥沙中铵态氮和硝态氮流失主要以铵态氮的形式流失,主要原因是铵态氮带有正电荷而更容易被土壤胶体吸附而随侵蚀泥沙流失^[29]。此外,本研究中雨季蔬菜地地表径流中铵态氮和硝态氮流失量高达 $2011.7\text{ g}\cdot\text{hm}^{-2}$ 和 $17430.9\text{ g}\cdot\text{hm}^{-2}$,远大于杨任翔等^[30]对同地区甘蔗坡地养分流失量。主要原因是蔬菜生长期短、复种指数高、施肥量大且频繁^[31]。

叶菜类处理坡面地表径流和侵蚀量均显著小于果菜类处理,其中坡面径流量仅为果菜类的78.8%(表3),二者的差异主要表现在蔬菜生长后期(图2



不同小写字母表示不同处理在 5% 水平上差异显著

图 4 不同处理下降雨等级坡面径流、侵蚀及其养分流失量分布特征

Fig. 4 Distribution characteristics of slope runoff, erosion, and nutrient loss at different rainfall levels under different treatments

和 3), 果菜类蔬菜坡面地表径流中氮素流失量是叶菜类蔬菜的 1.56 倍。汤宏等^[21]研究不同蔬菜类型对蔬菜地土壤养分径流损失发现, 果菜类(茄子)氮流失量均高于叶菜类(白菜和甘蓝), 分别是白菜和甘蓝的 1.98 倍和 1.41 倍。Wang 等^[3]研究也指出果菜类蔬菜的径流中氮素损失分别是叶菜类蔬菜和茎/根菜类蔬菜的 2.60 倍和 2.31 倍。一方面, 这是由于果菜类(茄子和辣椒)处理蔬菜生长期地表覆盖度较小(<60%), 而叶菜类(油麦菜和红薯叶)处理下坡面植被覆盖度整体较高, 尤其是蔬菜中后期超过 80%, 地表覆盖度高, 可以减小雨滴动能, 削弱对坡面的击溅^[32,33], 从而减少地表径流和侵蚀及其养分流失; 另一方面与蔬菜类型间氮肥施用量的差异有关^[34]。此外, 蔬菜地养分流失除地表径流和泥沙的携带外, 在非超渗产流情况下, 还包括壤中流携带的养分流失^[35,36]。Wang 等^[36]研究玉米生育期氮素地表径流和壤中流损失发现, 壤中流占 44.96%~88.87%。徐曼等^[37]研究发现, 旱坡地油菜-玉米轮作下氮流失以壤中流途径为主, 壤中流中全氮流失量是地表径流的 7.59~38.76 倍。但 Ma 等^[17]研究指出蔬菜地中地表径流的溶解态氮流失量是壤中流中养分流失量的 10.77~271.25 倍不等。表明蔬菜地坡面径流侵蚀及养分流失较为复杂, 但本文中仅分析了地表径流中铵态氮和硝态氮流失, 并未分析蔬菜地壤中流的养分流失特征, 在今后的研究中需

要加强壤中流对蔬菜地养分流失的影响。

3.2 降雨对蔬菜地土壤侵蚀及氮素流失的影响

降雨是坡面侵蚀发生和发展的主要动力, 坡耕地土壤侵蚀及养分流失实际上是表层土壤与降雨、径流相互作用的结果^[38,39]。不同处理下第二季蔬菜地表径流、侵蚀及其氮素养分流失量高于第一季蔬菜(表 3), 主要原因之一是不同蔬菜种植季间降雨分布不同, 第二季(7~9 月)降雨总量较大(570.0 mm)且降雨强度高(图 1), 降雨分布越集中其引起的侵蚀量越大^[39], 这与 Shan 等^[23]和邓华等^[40]研究结果相一致。次降雨下, 叶菜类和果菜类蔬菜地坡面径流、侵蚀量和氮素养分流失量主要集中在 06-03~06-16(25.0%~37.5%和 23.2%~32.8%)和 07-22~07-29(28.6%~41.3%和 24.3%~31.2%)这两个时期的侵蚀性降雨(图 2 和 3)。张林等^[41]研究发现, 丰水期强降雨是土壤养分输出的主要驱动, 其降雨径流贡献了雨季 88% 的总氮和 90% 的总磷流失。降雨量和最大 30 min 降雨强度是影响蔬菜地坡面土壤侵蚀及养分流失的最重要因子。坡面产流产沙量随降雨量的增大而增大^[42,43], 杨丽霞等^[44]研究发现, 随雨强增加蔬菜地坡面径流量及磷素流失量增大, 大雨强下总磷流失量是中雨强的 9~10 倍, 小雨强的 20 倍。徐捷等^[16]研究发现单次暴雨下硝态氮流失量占种植期间(5 次侵蚀性降雨)总流失量的 57.16%~67.60%。本文的结果与其不同, 这与各

降雨等级的降雨频次和降雨量等差异较大有关。本文中,大雨降雨等级是引起缓坡蔬菜地土壤侵蚀及养分流失的主要降雨等级,其次是暴雨和中雨,分别贡献了 29.58% ~ 46.68%、24.54% ~ 36.79% 和 24.01% ~ 39.13% 的流失量(图 4),说明高强度降雨易发生养分流失^[45]。因此,应加强高强度降雨时期蔬菜地水土流失的管控。

4 结论

(1) 叶菜类和果菜类蔬菜随地表径流流失的氮素(铵态氮和硝态氮)养分是泥沙流失的 10.17 ~ 11.46 倍,其中硝态氮是氮素的主要流失形态(>88%);果菜类(茄子-辣椒)和叶菜类(油麦菜-红薯叶)处理下坡面地表径流侵蚀及氮素流失均集中在 6 月和 7 月,尤其是集中在第二季蔬菜种植期。果菜类蔬菜地的地表径流、侵蚀量及氮素养分流失量显著高于叶菜类。

(2) 次降雨下,不同处理下坡面地表径流、侵蚀及其铵态氮和硝态氮养分流失在蔬菜生长期呈波动变化,且流失量主要集中在几场典型降雨。整体上第一季蔬菜地表径流和侵蚀泥沙中硝态氮和铵态氮流失量及含量低于第二季蔬菜。次降雨下果菜类地表径流、侵蚀量及铵态氮、硝态氮流失量整体上大于叶菜类,二者差异在第二季蔬菜中后期(8~9月)尤为明显,其中侵蚀量及其铵态氮、硝态氮流失量分别是叶菜类的 1.01 ~ 23.31、1.03 ~ 12.99 和 1.11 ~ 38.97 倍。

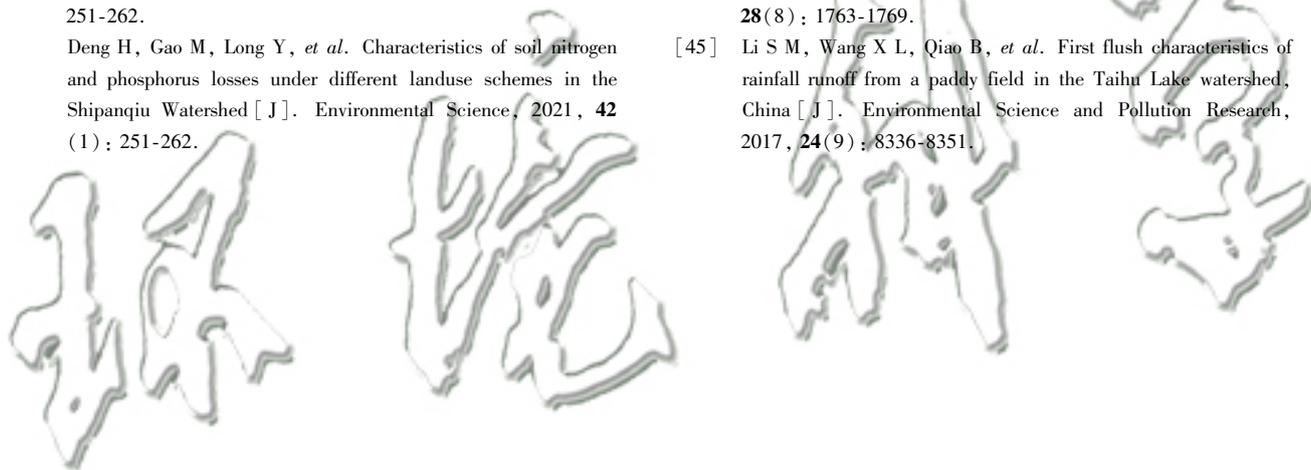
(3) 蔬菜地坡面地表径流、侵蚀及其铵态氮和硝态氮养分流失与降雨量关系最为密切,其次是 I_{30} ,均呈极显著正相关关系。不同处理下,叶菜类处理坡面径流、侵蚀及铵态氮和硝态氮流失主要由大雨和暴雨降雨等级贡献,占总流失量的 29.58% ~ 37.53% 和 27.63% ~ 37.36%;而果菜类处理主要来源于中雨和暴雨,占总流失量的 26.70% ~ 37.30% 和 35.61% ~ 46.68%。

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