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不同雨强下坡地氮流失特征

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摘要:试验采用模拟降雨手段,对总氮、铵氮和硝氮流失量过程曲线及三者的浓度百分比变化规律进行分析总结,获得以下结论:(1)降雨过程中,随着降雨强度的增加,氮流失的浓度和流失总量都会相应增加,在覆盖度较小时,雨强对氮流失浓度和流失总量起决定作用。(2)径流量随时间延长的增加趋势十分明显,径流中流失的总氮浓度随着时间延长没有明显变化,但是流失量却呈上升趋势。铵氮和硝氮流失浓度随着时间的变化规律,主要表现为径流前期浓度较高,随着降雨时间的延长,浓度趋于稳定或减小,后期则又有所上升。(3)与"蓄满"、"超渗"两种径流方式相对应,氮流失类型也有两种:坡地产生"蓄满"径流时,氮流失中可溶性氮流失较多;坡地产生"超渗"径流时,则氮流失中不可溶性氮流失所占比例增加,但是两种情况下,均是以可溶性氮流失为主,其中又以硝氮流失所占比例最大。坡度较小的情况下,次降雨过程中,不溶性氮占总氮流失量的百分比随时间延长而增加。

关键词:面源污染;降雨;径流;氮流失
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Research on characteristics of nitrogen loss in sloping land under different rainfall intensities

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Abstract: Non-point source pollution has been one severe environmental problem over world and was concerned and studied actively. Developed agriculture brought on the loss of fertilizer and pesticide which include much nitrogen and phosphorus. These contaminations led to the eutrophication of water body. However, there are several main factors affecting nitrogen loss such as rainfall intensity, slope, coverage ratio and so on. The factors effected nitrogen loss mainly by influencing runoff, in other words, the polluting ways of nitrogen loss to water would be reflected by nitrogen loss trend in runoff under different conditions.

In order to simulate the nitrogen loss characteristics during crops natural growing processes, according to given conditions such as rainfall intensity, slope and coverage, the experiments of adopting artificial simulated rainfall were designed. The experiments were conducted from August in 2005 to January in 2006 and carried in WSBRZ type automatic control glasshouse in Zhejiang University. There were two wooden runoff troughs with slopes 14 and 21, and they were filled

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with soil which was taken from Qingshan lake valley in Lin'an city. Cabbages were planted to provide different coverages based on the experiment design. In each rainfall process, 15 runoff samples were collected separately per minute or every two minutes in order. Following on, the runoff samples of 15 were analyzed in the lab, and the concentrations of TN, NH_4^+-N and NO_3^--N were respectively measured in 24 hours.

Artificial simulated rainfalls of 15 were conducted during the whole experiment. According to the experiment purpose, 6 rainfalls were selected from 15 simulated rainfalls and separated into three groups, while each group has two rainfalls with same slope and coverage and different rainfall intensities. Then, experiment data were analyzed in two ways. Firstly, by charting the curve of nitrogen loss in each group with increasing time, the gradients and numerical values of curves on the same chart were compared with each other respectively, to find out the differences between effects of different rainfall intensities on the nitrogen loss. Secondly, the changing trends of TN, NH_4^+-N and NO_3^--N concentration with increasing time were compared with each other, in order to get the relations among the concentration, time, and rainfall intensity. It could be inferred that NO_3^--N with bigger percentage was the main component in dissolved nitrogen distinctly.

The study was based on analyzing the experiment data from artificial simulated rainfalls on three indices such as TN, NH_4^+-N and NO_3^--N. Results in the study were summarized as following: ① the changes of TN concentration in runoff were inapparent with increasing time. However, the total loss content of TN increased evidently because of increasing runoff. Some specifically rules of NH_4^+-N and NO_3^--N concentration were discovered in loss with increasing time. The rules were that in early stage the concentration was high in runoff, in middle stage the concentration reduced or kept stabilization, and in the end the concentration reascended. ② there were two forming causes of runoff, correspondingly, there were two types of nitrogen loss. One type of nitrogen loss contained more dissolved nitrogen and the other type contained more undissolved nitrogen. Dissolved nitrogen was the main form in two types of nitrogen loss, while NO_3^--N was the main component in dissolved nitrogen. The loss percentage of undissolved nitrogen increased with increasing time under slope < 15 degrees. The loss percentages of undissolved nitrogen increasing suggested that re-pollution of nitrogen loss was very important and should be paid more attention to. Re-pollution of nitrogen loss was mainly caused by stronger rainfall intensities. The runoff patterns, which influenced the percentage of undissolved nitrogen loss, changed with different rainfall intensities. However, the loss of undissolved nitrogen was the major reason to non-point source re-pollution.

Key Words: non-point source pollution; artificial simulated rainfall; runoff; nitrogen loss

农田的面源污染主要是指降雨径流携带所施肥料中氮磷等营养元素进入水体，在这一过程中，影响面源污染程度的有两个方面：降雨径流过程和径流对氮磷的载运能力。降雨过程中，径流过程曲线以及不同时段所携带氮磷流失量的变化特征可以很好反映降雨对农田周围的地下水或湖泊水等造成的面源污染程度。

目前，对于农田氮磷径流损失的研究手段主要有两种：一种是通过较长时间的实际观测和定量分析，建立地表径流量与含氮、磷量的相关关系[1]；另一种则是利用野外或室内人工降雨试验获得有关参数以开展定量研究[2]。后一种研究手段由于条件能够控制而更加利于定量化。目前，国内外对农田坡地面源污染都进行了很多研究，主要集中在污染物的流失形态[3~11]以及各种耕作方式对面源污染的影响，而针对降雨过程中污染物流失形态的变化规律方面的研究比较少见，因此本试验在室内进行坡地人工模拟降雨，结合降雨径流和氮载运两个方面，采用单因素着手多因素分析的方法，综合分析整个降雨过程中氮元素随径流流失的过程，进行相应的曲线拟合，获得降雨对农田面源污染的影响规律。

1　试验设计与过程

模拟降雨试验于 2005 年 8 月 ~ 2006 年 1 月在浙江大学的 WSBRZ 型自控玻璃温室内进行。试验用土取自浙江省临安市青山湖流域低山丘陵区典型土壤，土壤类型为红黄壤，土壤容重见表 1。试验采用两个相同的木制径流试验槽，长、宽、高分别为 2、1、0.5m，分别设成 14°和 21°两个坡度，槽底以支架实现坡度的变换，

槽底端嵌有边缘高 5cm 的铁制集水槽，试验槽内土壤深度为 0.5m。模拟降雨装置是压控双向侧喷式人工模拟降雨装置，由有两个三角架支撑的 4m 高的钢管组成，与水源相连一端装有压力表和阀门，在土槽周边还安置有 6 个雨量标定桶以计算降雨均匀系数。模拟试验的降雨强度根据青山湖流域的气候资料确定，模拟降雨的间隔为 10d。

表 1 土壤容重

Table 1 Soil density

土壤深度 Soil depth (cm)	0 ~ 10	10 ~ 20	20 ~ 30	30 ~ 40	40 ~ 50
土壤容重 Soil density (g/cm^3)	1.13	1.14	1.15	1.16	1.19

土槽内种植白菜品种为早熟 5 号杂交一代，随着植株的生长变化，试验槽内地表覆盖度随之变化，试验选择适合的植株生长期即适合的覆盖度时期进行模拟降雨，整个试验期间共更替植株 3 代。由于两个试验槽的坡度不同，降雨强度和覆盖度条件完全可以符合试验设计的对比要求。

次降雨过程中，待径流产生时，记录径流产生时刻，并且在产流后以 1min 或 2min (据实际降雨情况而定) 为 1 个单位时间段，分别收集每一时间段内所产径流，降雨历时共 15 个单位时间段，在降雨停止后记录径流延续时间，收集延续的产流，并且测定每一时间段内径流和延续径流的体积。每场降雨过程中收集的径流样品 (5 个径流样品) 立即带回实验室进行含氮量的测定，主要测定 3 个指标：总氮 (参照 GB11894-1989 的碱性过硫酸钾消解紫外分光光度法)、硝氮 (参照 GB11894-89 的经滤膜后紫外分光光度法)、铵氮 (参照 GB/T8538-1995 的靛酚蓝比色法)。

2 结果与分析

根据试验中每场降雨的不同发生条件，即不同降雨强度，不同坡度，不同植被覆盖度等，设计出相对应的试验方案，在 15 场模拟降雨试验里，以坡度和覆盖度相同，降雨强度不同为分组要求，选取 6 场降雨的试验数据分成 3 组对比试验，然后分组将每场降雨过程中，径流里总氮，铵氮和硝氮的流失量随着降雨时间的推移而变化形成的过程曲线绘制在同一图中，进行曲线趋势的对照和流失量的大小比较。

另外，在每组对比降雨里选取一场降雨，共 3 场降雨，再根据每场降雨过程中具有代表性的 3 个时间点 (依降雨时间长短来定) 的总氮、铵氮和硝氮的浓度，分析铵氮和硝氮各占总氮的百分比，以及不溶性氮所占总氮百分比随时间变化的情况，揭示径流流失引起的氮流失浓度的潜在变化规律对面源污染的贡献本质。

2.1 径流中总氮、铵态氮、硝态氮流失量过程曲线及讨论分析

试验结果以总氮、铵氮和硝氮含量 3 个指标进行总体比较，再对分好的 3 组 a、b、c 进行组内各指标的比较，各图中 a、b、c，分别是对比试验的总氮，铵氮和硝氮的流失量随时间的过程曲线图。

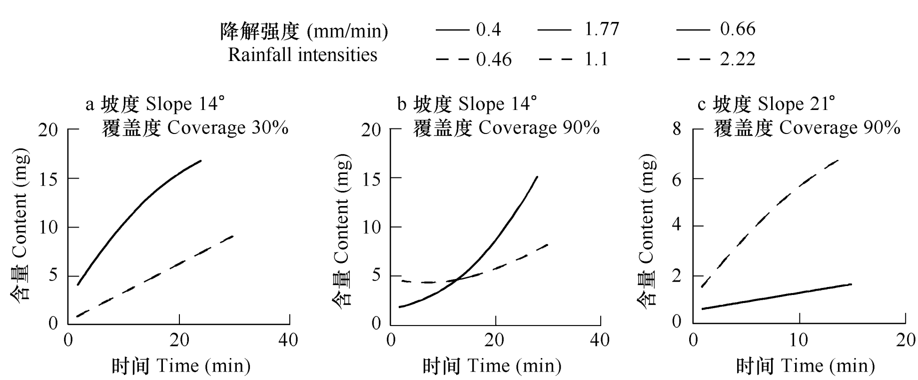

图 1 不同降雨强度下总氮流失量随时间变化的过程曲线

Fig. 1 Curve of TN loss changes with increasing time under different rainfall intensities

表 2　不同雨强下总氮流失量随时间变化的方程式

Table 2　Equations of TN loss changes and time under different rainfall intensities

雨强 Rainfall intensity (mm/min)	方程式 Equation	R^2
0.4	$y = -0.014x^2 + 0.9283x + 2.4178$	0.9871
0.46	$y = 6\times10^{-5}x^2 + 0.2919x + 0.3134$	0.9531
1.77	$y = 0.0253x^2 - 0.1417x + 4.5022$	0.951
1.1	$y = 0.0607x^2 + 0.0979x + 1.6431$	0.9782
0.66	$y = -0.0005x^2 + 0.0818x + 0.4872$	0.9712
2.22	$y = -0.0104x^2 + 0.5954x + 0.9763$	0.9733

不同降雨强度下总氮流失量随时间变化的过程曲线和方程式见图 1 和表 2。如图所示,3 组对比试验的结果都显示,总氮流失量随时间的延长而增大,而且过程曲线陡峭,增加幅度较大。其中图 b 与图 a 相比,覆盖度和雨强都增加,但是雨强的增大明显掩盖了覆盖度对流失量的影响,最终结果表现为流失量仍然增大且趋势明显。图 a 和图 b 说明,由于试验模拟的是植被在自然生长过程中降雨条件下径流产生情况,自然状态下,前一场降雨导致的地表细沟的良好发育,非常利于后来降雨时径流的产生,因此出现高强度降雨条件下的流失量明显少于低强度降雨。

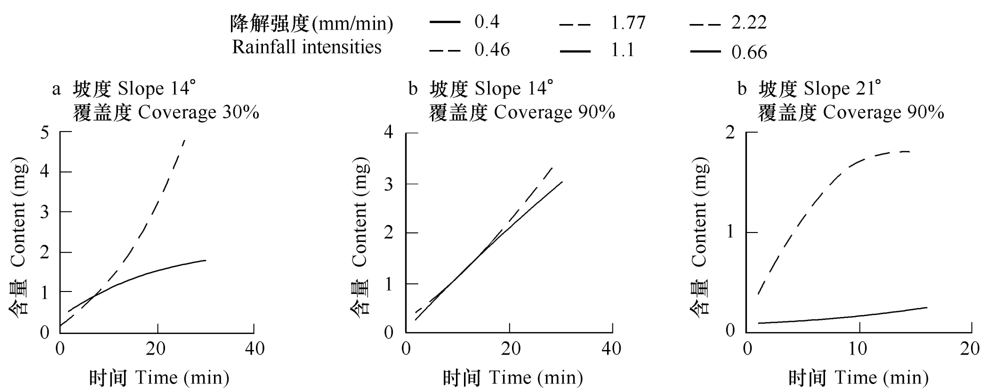

图 2　不同降雨强度下铵态氮流失量随时间变化的过程曲线

Fig. 2　Curve of NH_4^+-N loss changes with increasing time under different rainfall intensities

表 3　不同雨强下氨态氮流失量随时间变化的方程式

Table 3　Equations of NH_4^+-N loss changes and time under different rainfall intensities

雨强 Rainfall intensity (mm/min)	方程式 Equation	R^2
0.4	$y = -0.0011x^2 + 0.0788x + 0.3897$	0.8607
0.46	$y = 0.0044x^2 + 0.0643x + 0.1046$	0.9716
1.77	$y = 0.004x^2 + 0.1608x + 0.1787$	0.946
1.1	$y = -0.0025x^2 + 0.2353x + 0.0283$	0.92
0.66	$y = 0.0003x^2 + 0.0049x + 0.0844$	0.9504
2.22	$y = -0.0085x^2 + 0.2563x - 0.1088$	0.9591

不同降雨强度下铵态氮流失量随时间变化的过程曲线和方程式见图 2 和表 3。图 a 可知,铵氮作为可溶性氮,其流失量及过程曲线的陡峭度受雨强影响较大,雨强较大时增幅比较明显。图 b 是覆盖度 90% 的条件下可知,不同雨强下铵氮在流失过程中径流量趋势线一致,说明覆盖度较高的情况下雨强对可溶性铵氮的作用效果并不明显。图 c 是坡度 21°的条件下得出的,坡度的增大,强化了由于雨强的增加而产生的作用效果,二者差距十分明显。

不同降雨强度下总氮流失量随时间变化的过程曲线和方程式见图 3 和表 4。图 3 中 a 和图 2 中 a 因为同

为可溶性氮,曲线走势很相像,但是在流失量的绝对值上还是硝态氮较多,这跟梁新强[2]等研究的水稻田径流流失结果相符,说明坡地径流流失在雨量较小时,并不以物理侵蚀为主,而是以类似于水稻田的'蓄满'径流流失为主。图 3 中 c 和图 2 中 c 在曲线走势上也很相像,同样在流失量的绝对值上是硝态氮较多。

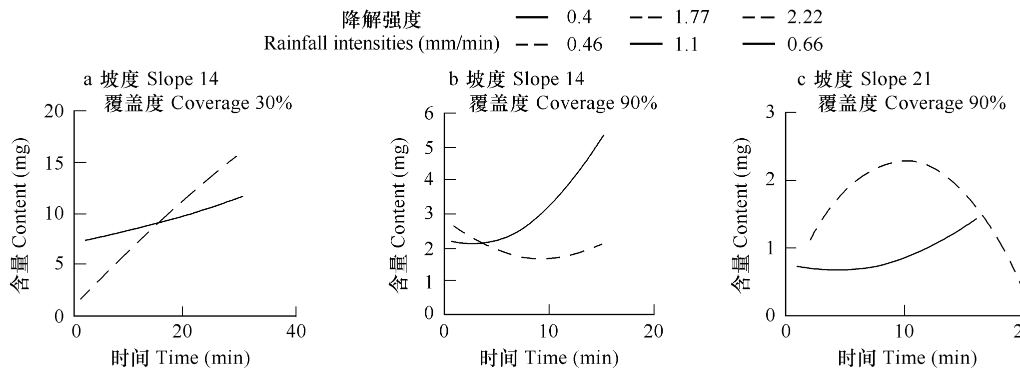

图 3 不同降雨强度下硝态氮流失量随时间变化的过程曲线

Fig. 3 curve of NO_3^- -N loss changes with increasing time under different rainfall intensities

表 4 不同雨强下硝态氮流失量随时间变化的方程式

Table 4 Equations of NO_3^- -N loss changes and time under different rainfall intensities

雨强 Rainfall intensity (mm/min)	方程式 Equation	R^2
0.4	$y = 0.0013x^2 + 0.1107x + 7.1046$	0.8438
0.46	$y = -0.0024x^2 + 0.568x + 0.8147$	0.9392
1.77	$y = 0.0079x^2 - 0.0565x + 2.8141$	0.8225
1.1	$y = 0.0217x^2 - 0.1248x + 2.2676$	0.7894
0.66	$y = 0.0055x^2 - 0.0445x + 0.7521$	0.9304
2.22	$y = -0.0267x^2 + 0.6985x + 0.4424$	0.8007

降雨产流和入渗过程中,存在超渗产流和蓄满产流两种方式,当降雨强度小于或等于土壤入渗率时不产流,并以降雨强度向下入渗;当降雨强度大于入渗强度时,则形成超渗产流;当土壤最大蓄水量小于累积入渗量时,则形成蓄满产流[3]。依据径流的两种方式把氮流失分为与其相对应的两种类型:即以超渗产流也就是物理侵蚀泥沙携带为主的氮流失类型和以蓄满产生径流引起的氮流失类型。其中前者不溶性氮的流失比例比后者要高。在坡地或旱地径流中,氮磷素的流失大多由于雨水的直接冲蚀引起的,因此泥沙结合态流失的氮的量是相当可观的[4],这可以理解为是超渗引起的氮流失类型。试验由于设定的雨强大小范围较广,可以涵盖两种氮流失类型。

分析结果表明,当雨强较小时,径流以蓄满为主,流速较慢,可溶性氮可以更多的溶解进入径流,所以雨强越小,流失掉的可溶性氮占总氮的比例就越高。反之,雨强较大时,径流以超渗为主,流速较快,不溶性氮由于物理作用而被径流冲刷带走,所以总氮流失量里不溶性氮所占比例就提高。此外,坡度、覆盖度等因素则以影响径流方式为先,进而影响氮流失类型。

2.2 总氮、铵氮和硝氮浓度之间比例变化情况分析

从每组对比试验里选择 1 场降雨,每场降雨过程中选取具有代表性的 3 个时间点(根据降雨历时的长短来确定),通过对这 3 个时间点上总氮、铵氮和硝氮 3 个指标之间的的浓度百分比变化规律的总结,进而推导出一般情况次降雨条件下的氮流失浓度变化趋势特征。从试验数据可以看出,次降雨过程中,总氮流失量和铵氮、硝氮流失量之间的比例关系随着时间变化有一定的规律可寻。数据如表 5 和表 6 所示。

表 5 和表 6 可以说明,径流流失过程中氮主要以可溶性氮的流失为主,其中可溶性氮又以硝氮流失所占比例最大。坡度较小时随时间的变化,各氮浓度指标均呈下降趋势,而径流流失中可溶性氮的比例也随时间

减小,这说明随着降雨时间的延长,不溶性氮占总氮流失的百分比将逐渐增加,且雨强的增大会影响到不溶性氮比例的增长幅度,表现为雨强越大,增幅越大。这一点还可以说明,目前面源污染的治理中单纯考虑一次污染是不够的,不溶性氮的缓释性决定了要从长远角度分析面源污染的危害程度,二次污染是不容忽视的。

表 5 不同雨强下各氮指标随时间变化情况

Table 5 Changes of every nitrogen index with increasing time under different rainfall intensities

雨强 Rainfall intensity (mm/min)	时间 Time (min)	总氮浓度 TN concentration (mg/L)	铵氮浓度 NH_4^+-Nconcentration (mg/L)	硝氮浓度 NO_3^--N concentration (mg/L)
0.4	10	4.65	0.56	3.84
	20	4.65	0.48	3.05
	30	4.77	0.47	2.99
0.66	5	3.15	0.41	2.35
	10	3.08	0.39	1.71
	15	2.91	0.44	2.02
1.1	5	4.64	1.19	2.95
	10	4.49	1.14	2.31
	15	4.44	0.83	1.49

表 6 不同雨强下各氮指标占总氮百分比随时间变化情况

Table 6 Changes of every nitrogen percentage in TN with increasing time under different rainfall intensities

雨强 Rainfall intensity (mm/min)	时间 Time (min)	铵氮占总氮比例 Percentage of NH_4^+-N in TN	硝氮占总氮比例 Percentage of NO_3^--N in TN	不溶性氮占总氮比例 Percentage of undissolved nitrogen in TN
0.4	10	0.12	0.83	0.05
	20	0.10	0.66	0.24
	30	0.1	0.63	0.27
0.66	5	0.13	0.75	0.12
	10	0.13	0.62	0.25
	15	0.15	0.70	0.15
1.1	5	0.26	0.64	0.1
	10	0.25	0.51	0.24
	15	0.19	0.34	0.47

3 结论

综上,从总氮、铵氮和硝氮 3 个指标着手,对试验数据中氮流失量过程曲线及三者的浓度百分比变化规律进行分析总结,获得以下结论:

(1)降雨过程中,随着降雨强度的增加,氮流失的浓度和流失总量都会相应增加,在覆盖度较小时,雨强对氮流失浓度和流失总量起决定作用。

(2)径流中流失的总氮浓度随着时间延长没有明显变化,但是流失量却呈上升趋势,原因在于径流量随时间延长的增加趋势十分明显。铵氮和硝氮作为可溶性氮,它们的流失浓度随着时间的变化有一定的规律性,主要表现为径流前期浓度较高,随着降雨时间的延长,浓度趋于稳定或减小,后期则又有所上升。

(3)与两种径流方式相对应,氮流失类型也有两种:坡地产生"蓄满"径流时,氮流失以可溶性氮流失较多;坡地产生"超渗"径流时,则氮流失中不可溶性氮流失所占比例增加。但是两种情况下,均是以可溶性氮流失为主,其中又以硝氮流失所占比例最大。其中坡度较小的情况下,次降雨过程中不溶性氮占总氮流失量的百分比随时间的延长而增大。

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