Chinese Journal of Applied Ecology, Nov. 2019, 30(11): 3771-3776 DOI: 10.13287/j.1001-9332.201911.021

施氮量对夏玉米籽粒灌浆特性和营养品质的影响

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摘 要 合理施氮可显著提高夏玉米籽粒灌浆速率,增加产量,改善品质.本试验以登海518(DH518)和郑单958(ZD958)为供试材料,大田条件下设置不施氮(N_0)、少量施氮(N_1,129 kg N·hm^{-2})、适量施氮(N_2,184.5 kg N·hm^{-2})和过量施氮(N_3,300 kg N·hm^{-2})4个施氮量处理,研究施氮量对夏玉米籽粒灌浆特性和籽粒品质的影响.结果表明:不施氮处理玉米的籽粒灌浆受抑制,粒重减小,产量显著降低;随着施氮量增加,两品种的籽粒平均灌浆速率增加,粒重和产量显著增加,N_1处理较N_0增产16.4%~57.2%,N_2处理较N_0增产35.8%~65.1%.N_0处理的籽粒粗蛋白、可溶性糖和总淀粉含量及支链/直链淀粉(支/直)降低,粗脂肪含量增加;DH518品种N_2处理较N_0、N_1处理的粗蛋白、可溶性糖和总淀粉含量分别增加32.5%、6.5%,19.9%、9.5%和8.9%、5.2%,且支/直升高;ZD958品种N_2处理较N_0、N_1处理的粗蛋白、可溶性糖和总淀粉含量分别增加16.9%、7.8%,30.5%、14.8%和11.5%、5.7%,支/直升高;两品种N_2处理的粗脂肪含量较N_0和N_1降低4.8%~12.3%.但是,过量施氮(N_3)较N_2处理夏玉米产量降低,籽粒品质下降.可见,合理施氮可促进夏玉米籽粒灌浆,增加粒重,提高产量,改善品质.

关键词 夏玉米; 施氮量; 产量; 籽粒灌浆特性; 籽粒营养品质

Effects of nitrogen application rate on grain filling characteristics and nutritional quality of summer maize.

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Abstract: Suitable nitrogen application rate can significantly increase grain filling rate and yield and improve nutritional quality. Denghai 518 (DH518) and Zhengdan 958 (ZD958) were used as experimental materials in this study. A field experiment with four treatments, no nitrogen treatment (N_0), decrement nitrogen application rate (N_1, 129 kg N·hm^{-2}), suitable nitrogen rate (N_2, 184.5 kg N·hm^{-2}) and excessive nitrogen rate (N_3, 300 kg N·hm^{-2}), was conducted to explore the effects of nitrogen fertilization on grain filling parameters and nutritional qualities of summer maize. Results showed that grain filling characteristics, grain dry weight, and yield in N_0 treatment was decreased. With increasing nitrogen application rate in the suitable range, average filling rate, grain dry weight, and yield increased. Grain yield of two hybrids in N_1 and N_2 treatments was higher than that of N_0 by 16.4%-57.2% and 35.8%-65.1%, respectively. Grain protein, soluble sugar, starch contents and the ratio of amylopectin and amylase contents were lower and crude fat content was higher in N_0 treatment. Grain protein content, soluble sugar content and starch content in N_2 of DH518 were higher than that of N_0 and N_1 by 32.5% and 6.5%, 19.9% and 9.5%, 8.9% and 5.2%, and the ratio of amylopectin and amylose contents was increased. Grain protein, soluble sugar and starch contents in N_2 of ZD958 were higher than that of N_0 and N_1 by 16.9% and 7.8%, 30.5% and 14.8%, 11.5% and 5.7%, and the ratio of amylopectin and amylase contents was increased. Crude fat content in N_2 of both hybrids decreased significantly by 4.8%-12.3% than that of N_0 and N_1. However, yield and nutritional quality was increased in N_3 treatment than that of N_2. Our results suggested that suitable nitrogen rate could enhance grain filling, grain weight, and grain nutritional

本文由国家重点基础研究发展计划项目(2015CB150404)、国家现代农业产业技术体系项目(CARS-02-18)和山东省"双一流"奖补资金(SYL2017YSTD02)资助 This work was supported by the National Basic Research Program of China (2015CB150404), National Modern Agricultural Technology & Industry System (CARS-02-18) and Funds of Shandong "Double-Tops" Program (SYL2017YSTD02).
2018-11-19 Received, 2019-09-12 Accepted.
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quality.

Key words: summer maize; nitrogen application rate; grain yield; grain filling characteristics; grain nutritional quality.

黄淮海地区是我国玉米主产区之一,生产的玉米大部分用于饲料加工,其营养品质至关重要.合理增施氮肥可有效提高夏玉米产量,同时也是改善玉米品质的重要途径[1-2].在适宜施氮范围内,增施氮肥能够提高籽粒灌浆速率,促进开花后光合产物向籽粒运转,从而提高粒重,实现增产[3-6].增施氮肥也可增加籽粒中蛋白质、淀粉和可溶性糖含量,降低粗脂肪含量,改善品质[2,7].施氮量过低,灌浆速率下降,营养器官氮素向籽粒中的转运减少,籽粒干重降低,籽粒品质下降[8-10].因此,本试验在大田条件下设置不同施氮量处理,研究施氮量对夏玉米籽粒灌浆和籽粒品质的影响,以期为黄淮海夏玉米高产优质高效生产提供理论依据.

1 材料与方法

1.1 试验材料与试验设计

本试验于 2016—2017 年在泰安市大汶口镇进行,以'郑单 958'(ZD958)和'登海 518'(DH518)为供试材料,设置 4 个不同施氮量处理,分别为施 0、129、184.5 和 300 kg N · hm^{-2}(尿素,含 46% N),依次记作 N_0、N_1、N_2 和 N_3,分别代表不施氮、少量、适量和过量施氮,随机区组试验设计,播前、拔节、抽雄时期的施氮比例为 15∶50∶35.各试验处理的磷、钾肥施用量均一致,其中磷肥(过磷酸钙,含 17% P_2O_5)于播前施入 30 kg · hm^{-2},拔节施入 25.5 kg · hm^{-2};钾肥(氯化钾,含 60% K_2O)在播前、拔节、抽雄时分别施入 30、70.5、30 kg · hm^{-2}.两年试验夏玉米均于 6 月中旬播种,行距 60 cm,小区面积均为 240 m^2,种植密度为 75000 株 · hm^{-2},10 月 1 日收获.

1.2 测定项目与方法

1.2.1 有效积温 气象资料由农情实时监测平台(http://www.nqssjc.com/)提供,第 i 天累积的有效积温为 $T=\sum[(T_{max}+T_{min})/2-10]$,其中:$T_{max}$和 T_{min}为第 i 天的最高气温和最低气温(10 ℃ < T_{min} < T_{max} < 35 ℃).

1.2.2 籽粒灌浆特性 玉米吐丝后选取吐丝一致的 50 株植株进行标记,开花后每隔 5 d 进行取样,每个处理选取 5 株,分别剥取玉米果穗中部的籽粒 100 粒,称鲜重,排水法测定籽粒体积;于烘箱 80 ℃烘干至恒量,称干重.平均灌浆速率(g · $℃^{-1}$)= 生理成熟期百粒干重/灌浆期有效积温;籽粒最大含水量到收获时的灌浆速率(g · $℃^{-1}$)=(收获时百粒干重-籽粒绝对含水量最大时的百粒干重)/籽粒绝对含水量最大到收获时的有效积温.

1.2.3 籽粒品质 成熟期取籽粒,于烘箱 50 ℃烘干至恒量后粉碎,采用凯氏定氮法测定粗蛋白含量(粗蛋白含量=籽粒全氮含量×6.25)[11];索氏提取法-残余法抽提 12 h 测定粗脂肪含量[11];蒽酮-硫酸比色法测定总淀粉和可溶性糖含量[12];双波长法测定支链、直链淀粉含量[13].

1.2.4 考种与测产 每小区收获玉米中间 3 行,共 30 个果穗,3 个重复,测定千粒重、含水量,计算实际产量(按 14.0%折算含水率).产量(kg · hm^{-2})= 有效公顷穗数×穗粒数×千粒重(g)/1000×(1-含水量)/(1-14.0%).

1.3 数据处理

采用 Excel 2003 和 SPSS 17.0 软件进行数据统计分析.采用单因素(one-way ANOVA)和 Duncan 法进行方差分析和多重比较($\alpha=0.05$),用 Pearson 法对籽粒含水量和籽粒品质进行相关分析.利用 SigmaPlot 10.0 软件作图.图表中数据为平均值±标准差.

2 结果与分析

2.1 施氮量对夏玉米产量的影响

不施氮处理显著降低夏玉米产量;在适宜范围内,产量随着施氮量的增加而增加,两年趋势一致.以 2016 年为例,DH518 品种 N_1 处理的产量较 N_0 显著增加 57.2%;N_2 处理的产量进一步提高,较 N_0 处理显著增加 65.1%;但是,过量施氮(N_3)较 N_2 处理降低1.5%.ZD958 品种 N_2、N_1 处理的产量较 N_0 分别增加 35.8%、24.8%,N_3 处理的产量较 N_2 降低 3.0%(图 1).

2.2 施氮量对夏玉米籽粒灌浆特性的影响

不施氮或少量施氮处理的生育进程推迟;2016 年,DH518 品种的 N_0、N_1 处理较 N_2 分别推迟 6、4 d,ZD958 品种的 N_0、N_1 处理较 N_2 分别推迟 3、1 d;2017年,两品种的N_0处理较N_2均延迟4 d,N_1

表 1　施氮量对夏玉米籽粒灌浆的影响

Table 1　Effects of different nitrogen application rates on grain filling of summer maize

年份 Year	品种 Variety	处理 Treatment	吐丝期 Silking stage	灌浆期有效积温 T_f (℃)	百粒重 100-KDW (g)	平均灌浆速率 Average filling rate (mg·℃$^{-1}$)	籽粒最大含水率的百粒重 100-KDW$_m$ (g)	籽粒最大含水量到收获时的灌浆速率 R_m (mg·℃$^{-1}$)
2016	DH518	N_0	08-05	683.6	28.8c	42.1	9.21c	73.8
		N_1	08-03	733.8	31.5b	42.9	12.02b	73.4
		N_2	07-30	765.2	32.9a	43.0	12.38a	77.3
		N_3	07-30	765.2	32.7a	42.7	12.16b	77.4
	ZD958	N_0	08-06	672.3	31.0c	46.1	8.62c	84.4
		N_1	08-04	683.6	31.7b	46.4	9.29b	84.5
		N_2	08-03	699.7	33.7a	48.2	10.14a	88.8
		N_3	08-03	699.7	33.5a	47.9	10.29a	87.5
2017	DH518	N_0	08-06	829.4	33.7c	40.6	11.12b	62.5
		N_1	08-03	846.0	34.8b	41.1	11.98b	63.2
		N_2	08-02	862.4	35.9a	41.6	12.54a	64.7
		N_3	08-02	862.4	35.7a	41.4	12.44a	64.4
	ZD958	N_0	08-08	754.5	33.8c	44.8	9.36b	67.7
		N_1	08-05	771.7	34.9b	45.2	10.54a	67.5
		N_2	08-04	785.9	35.8a	45.6	10.84a	69.1
		N_3	08-04	785.9	35.6a	45.3	10.92a	68.3

DH518：登海 518 品种 The variety of Denghai 518；ZD958：郑单 958 品种 The variety of Zhengdan 958. N_0：不施氮处理 No nitrogen treatment；N_1：施 129 kg N·hm^{-2} Application of 129 kg N·hm^{-2}；N_2：施 184.5 kg N·hm^{-2} Application of 184.5 kg N·hm^{-2}；N_3：施 300 kg N·hm^{-2} Application of 300 kg N·hm^{-2}. T_f：Effective accumulated temperature during filling stage；100-KDW：100-kernel dry weight；100-KDW$_m$：100-kernel dry weight at maximum water content；R_m：Filling rate between maximum water content and harvest. 同列不同字母表示同一年份同一品种不同处理间差异显著（$P<0.05$）Different letters in the same column meant significant difference among different treatments at 0.05 level of the same variety in the same year. 下同 The same below.

处理较 N_2 均延迟 1 d.随吐丝期的延迟，不同施氮量处理灌浆期的有效积温减少，百粒干重降低，表现为 $N_0<N_1<N_2\approx N_3$，两年趋势一致.同时，降低施氮量，夏玉米的平均灌浆速率和从籽粒最大含水量到收获时的灌浆速率下降.以 2016 年为例，DH518 品种 N_2 处理的灌浆期有效积温较 N_0、N_1 分别增加81.6和31.7 ℃，平均灌浆速率分别增加 2.1% 和 0.2%，从籽粒最大含水量到收获时的灌浆速率分别增加 4.7% 和 5.3%，百粒干重显著增加 14.2% 和 4.4%；ZD958 品种 N_2 处理的灌浆期有效积温较 N_0、N_1 分别增加 27.4 和 16.1 ℃，平均灌浆速率分别增加 9.5%和3.9%，籽粒最大含水量到收获时的灌浆速率分别增加 5.2% 和 5.1%，百粒干重显著增加 8.7%和 6.3%（表 1）.

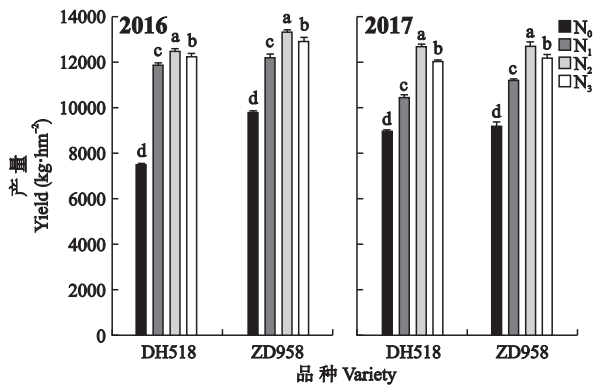


图 1　施氮量对夏玉米产量的影响

Fig. 1　Effects of different nitrogen application rates on grain yield of summer maize.

N_0：不施氮处理 No nitrogen treatment；N_1：施 129 kg N·hm^{-2} Application of 129 kg N·hm^{-2}；N_2：施 184.5 kg N·hm^{-2} Application of 184.5 kg N·hm^{-2}；N_3：施 300 kg N·hm^{-2} Application of 300 kg N·hm^{-2}. DH518：登海 518 品种 The variety of Denghai 518；ZD958：郑单 958 品种 The variety of Zhengdan 958. 不同字母表示同一品种不同处理间差异显著（$P<0.05$）Different letters meant significant difference at 0.05 level among different treatments in the same variety. 下同 The same below.

2.3　施氮量对夏玉米籽粒含水量的影响

收获时不施氮或降低施氮量处理的籽粒含水量高，N_2、N_3 处理间无显著性差异，两年趋势一致（图 2）.以2016年为例，收获时DH518品种 N_0、N_1 处理

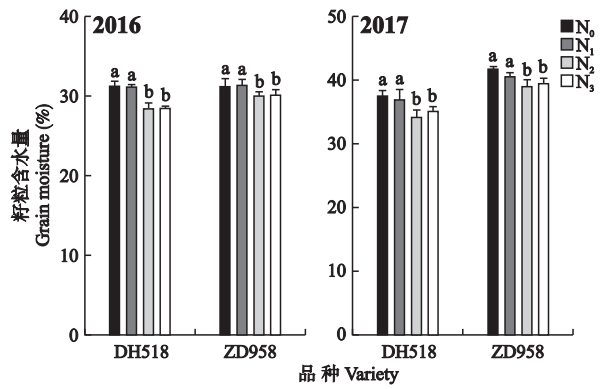


图 2　不同施氮量夏玉米收获时的籽粒含水量

Fig. 2　Grain moisture of summer maize at harvest in different nitrogen application rates.

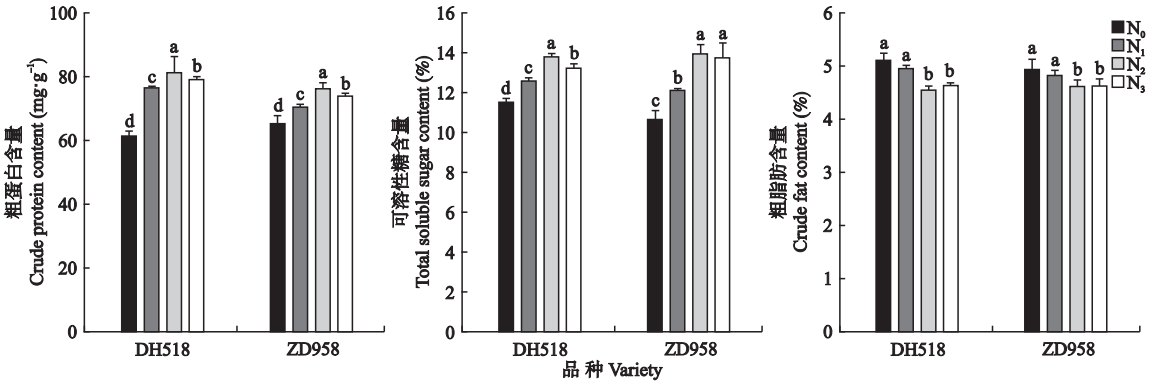


图 3 不同施氮量夏玉米籽粒的可溶性糖、粗蛋白和粗脂肪含量

Fig.3 Grain soluble sugar, crude protein and crude fat contents of summer maize in different nitrogen application rates.

的籽粒含水量较 N_2 升高 6.5%和 10.3%,ZD958 品种 N_0、N_1 处理的籽粒含水量较 N_2 升高 4.2%和 4.9%.

2.4 施氮量对夏玉米淀粉含量及其组分的影响

由表 2 可知,不施氮或降低施氮量总淀粉含量降低;在适宜范围内,总淀粉含量随着施氮量的增加而增加,总体趋势表现为 $N_2>N_3>N_1>N_0$.DH518 品种 N_2 处理的总淀粉含量较 N_0、N_1 分别增加 8.9%和 5.2%,N_2、N_3 处理间无显著性差异;ZD958 品种 N_2 处理的总淀粉含量较 N_0、N_1 分别增加 11.5%和 5.7%,过量施氮处理的总淀粉含量较 N_2 处理降低 1.8%.此外,不施氮或降低施氮量夏玉米籽粒中的支链淀粉含量显著降低,直链淀粉含量显著升高,支/直下降,其中不施氮处理支/直最低,两品种 N_0 处理的支/直较 N_2 分别下降 20.1%和 24.0%.

2.5 施氮量对夏玉米可溶性糖含量的影响

由图 3 可知,不施氮或降低施氮量夏玉米籽粒中可溶性糖含量降低;在适宜范围内,可溶性糖含量随着施氮量的增加而增加,两品种趋势一致.DH518 品种 N_2 处理的可溶性糖含量较 N_0、N_1 分别增加 19.9%和 9.5%;过量施氮可溶性糖含量有所降低,N_3 处理较 N_2 降低 4.0%.ZD958 品种 N_2 处理的可溶性糖含量较 N_0、N_1 分别增加 30.5%和 14.8%;N_2、N_3 处理间无显著性差异.

表 2 施氮量对夏玉米籽粒淀粉含量的影响

Table 2 Effects of different nitrogen application rates on grain starch content of summer maize

品种 Variety	处理 Treatment	总淀粉 Total starch (%)	支链淀粉 Amylopectin (%)	直链淀粉 Amylose (%)	支链淀粉/直链淀粉 Amylopectin/amylose
DH518	N_0	62.4c	41.4c	21.0a	1.97
	N_1	64.6b	44.4b	20.2ab	2.20
	N_2	68.0a	48.4a	19.5c	2.48
	N_3	67.2a	47.1a	20.1ab	2.35
ZD958	N_0	63.5d	40.6c	22.9a	1.77
	N_1	67.0c	44.6b	22.4ab	1.99
	N_2	70.8a	49.5a	21.2b	2.33
	N_3	69.5b	47.8a	21.7b	2.20

2.6 施氮量对夏玉米粗蛋白含量的影响

不施氮或降低施氮量夏玉米籽粒中粗蛋白含量降低;在适宜范围内,粗蛋白含量随着施氮量的增加而增加,两品种趋势一致.DH518 品种 N_2 处理的粗蛋白含量较 N_0、N_1 分别增加 32.5%和 6.5%;过量施氮粗蛋白含量降低,N_3 处理较 N_2 降低 2.3%;ZD958 品种 N_2 处理的粗蛋白含量较 N_0、N_1 分别增加 16.9%和 7.8%;过量施氮较 N_2 处理粗蛋白含量降低 3.0%(图 3).

2.7 施氮量对夏玉米粗脂肪含量的影响

不施氮或降低施氮量夏玉米籽粒中粗脂肪含量增加;随着施氮量的增加,粗脂肪含量降低,N_2、N_3 处理间无显著性差异,两品种趋势一致.DH518 品种 N_2 处理的粗脂肪含量较 N_0、N_1 降低 12.3%和8.1%;ZD958 品种 N_2 处理的粗脂肪含量较 N_0、N_1 降低 6.5%和 4.8%(图 3).

3 讨 论

施氮显著影响夏玉米的籽粒灌浆.粒重主要取决于灌浆速率,较高的平均灌浆速率是获得高粒重的前提[14-15],施氮可提高玉米籽粒的最大灌浆速率、灌浆速率最大时的生长量,增加灌浆渐增期、速增期和缓增期的持续时间,促进籽粒干物质的积累[4,9,16].也有研究表明,氮肥在玉米籽粒灌浆过程中的作用主要是通过灌浆前期的灌浆速率来影响籽粒建成,最终使百粒重增加[5].本研究表明,不施氮

处理的平均灌浆速率和籽粒含水率最大时到收获时的灌浆速率显著降低，产量显著降低；随施氮量的增加，平均灌浆速率和从籽粒含水量最大时到收获时的灌浆速率增加，粒重增加，进而产量显著提高；但是，过量施氮平均灌浆速率和籽粒含水量最大时到收获时的灌浆速率略有降低，产量下降.

适量增施氮肥可增加玉米、小麦籽粒中蛋白质的含量，促进籽粒中淀粉和脂肪酸的形成[17-20]，这可能与氮影响植物体内多种化合物的合成有关；降低施氮量，玉米体内的氮素积累量较低，碳氮代谢较慢，不利于有机化合物，尤其是蛋白质的合成[21].但也有学者认为，施氮可提高籽粒蛋白质含量，但降低了淀粉的含量[21].本研究表明，增加施氮量可提高籽粒中总淀粉的含量，优化支链淀粉和直链淀粉的比例，增加支/直，这支持了增加施氮量可增加总淀粉含量的观点.籽粒含水量显著影响籽粒品质.籽粒含水量低，籽粒易于贮藏、运输，玉米的商品品质提高[22-23].淀粉、支链淀粉和粗脂肪与生理成熟后籽粒脱水速率的直接通径系数为正值，淀粉、支链淀粉含量与籽粒脱水速率达到极显著正相关；籽粒含水量越高，籽粒品质越受影响[22-23].同时，籽粒含油量与生理成熟后籽粒脱水速率呈负相关[24].本研究表明，籽粒含水量与总淀粉、可溶性糖含量呈显著负相关，与粗脂肪含量呈显著正相关(表 3)，这与前人研究结果一致.不施氮或少量施氮处理到吐丝期的时间推迟，整个灌浆期的有效积温减少，收获时的籽粒含水量显著增加，这可能是导致籽粒品质下降的原因之一.在适宜范围内，随施氮量的增加，籽粒含水量降低，籽粒中粗蛋白、可溶性糖含量增加，总淀粉含量及其支/直增加，粗脂肪含量降低，品质改善；但过量施氮籽粒品质略有下降.

总之，合理施氮即可以提高籽粒平均灌浆速率和籽粒最大含水量到收获时的灌浆速率，降低收获时的籽粒含水量，增加粒重，提高产量；同时，也可增加籽粒中粗蛋白、可溶性糖含量，增加总淀粉含量及支/直，降低粗脂肪含量，改善品质.

表 3　籽粒含水量与籽粒品质的相关系数

Table 3　Correlation coefficients between grain moisture and grain quality

	籽粒含水量 Grain moisture	总淀粉含量 Total starch content	可溶性糖含量 Soluble sugar content
总淀粉含量 Total starch content	−0.995 * *		
可溶性糖含量 Total soluble sugar content	−0.982 *	0.988 *	
粗脂肪含量 Crude fat content	0.998 * *	−0.993 * *	−0.970 *

* $P<0.05$；* * $P<0.01$.

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