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Research Article

Study on Mechanism Experiments and Evaluation Methods for Water Eutrophication

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The process of water eutrophication involves the interaction of external factors, nutrients, microorganisms, and other factors. It is complex and has not yet been effectively studied. To examine the formation process of water eutrophication, a set of orthogonal experiments with three factors and four levels is designed to analyze the key factors. At the same time, with the help of a large amount of monitoring data, the principal component analysis method is used to extract the main components of water eutrophication and determine the effective evaluation indicators of eutrophication. Finally, the Bayesian theory of uncertainty is applied to the evaluation of the eutrophication process to evaluate the sample data. The simulation results demonstrate the validity of the research method.

1. Introduction

Currently, approximately 40% of lakes and reservoirs worldwide are affected by different degrees of eutrophication. Eutrophic lakes and reservoirs in China account, respectively, for 69.8% and 41.95% of the total [1–3]. Water eutrophication has become a major global environmental problem. Cyanobacteria bloom is a common ecological disaster in eutrophic lakes and reservoirs in most of the world [4, 5], and China is among the countries where the problem is the most serious and widely distributed [6, 7]. Therefore, it is of great significance to conduct effective research and scientific evaluation of water quality to prevent water pollution and ensure the safety of human water supplies [8, 9].

Water eutrophication is when large amounts of elements such as nitrogen, phosphorus, and potassium flow into the surface water with a slow flow rate and long renewal period, causing the growth of algae and other aquatic organisms so that the rate of organic production is far greater than the consumption rate, ultimately leading to the accumulation of organic matter in water and destruction of the aquatic ecological balance [10, 11]. At present, the traditional mathematical modeling methods to study the ecological process of lake eutrophication mainly involve the nutrient load model [12, 13], phytoplankton ecological model [14, 15], and ecological dynamic model [16, 17]. Vollenweider proposed the total phosphorus balance model to examine the influence of certain nutrient concentration changes on eutrophication ecological processes [18, 19]. Jørgensen et al. proposed an ecological model with carbon, nitrogen, and phosphorus as nutrients and floating plants as the central variable of the ecological model [20, 21]. Narasimhan et al. simulated the relationship of a watershed nonpoint source nutrient load and the characteristics of chlorophyll a concentration by building a valley eutrophication model of the Cedar river reservoir [22]. The four-stage theory of cyanobacteria bloom formation was also proposed by Kong et al. [23]. However, the formation mechanism of water eutrophication involves many parameters, some of which show high levels of nonlinearity and uncertainty, so the above models have difficulty describing the complex relationship of water nutrients, water parameters, and microbial factors, which is unfavorable for thorough analysis of the water quality status and it makes it difficult to assess the level of water eutrophication.

As the process of water eutrophication has greater uncertainty and complex interactions of each factor, we design an orthogonal experiment to analyze the key factors in water eutrophication and use the principal component analysis method to extract the principal components affecting water quality status, finally obtaining water eutrophication evaluation indexes. Then, the Bayesian method is used to evaluate the water quality situation of major lakes in our country, concluding that the water quality evaluation results of the mechanism analysis have high accuracy.

2. Experiment

During the formation process of water eutrophication, the water temperature (WT), illumination, total nitrogen, and total phosphorus have the greatest impacts on algae growth and reproduction. Accordingly, an experiment is designed to analyze these four factors, using an orthogonal approach to examine the degree of influence in the overall process of algae growth and reproduction and find the key factors that determine the input variables for evaluating water eutrophication.

2.1. Collection and Preparation of Water Samples. Experimental water samples were taken from Yuyuantan for the determination of total nitrogen and total phosphorus. After pretreatment and placing the water in a light incubator 20°C, at a light intensity of 6000 lx and a light dark ratio of 12 h : 12 h, the nitrogen was 1.445 mg/L and the phosphorus was 0.2 mg/L. Algae growth status and the cell density of algae were observed daily by microscope, and, when the algae cell density reached 10^6 cell/L, it could be used as the experimental algae (each group taken from the water samples).

2.2. Measurement of Chl_a. The experiment uses the M11 culture medium as a basis for media with a series of concentration gradients of nitrogen and phosphorus [24]. Calculating based on the algal cells' initial density of 10^5 cell/L, take a certain volume of algae species liquid to preculture in a 3500 r/min centrifuge for 5 minutes and then remove the supernatant and apply sterile water several times to remove the surface-adsorbed nitrogen and phosphorus. Then, centrifuge again, remove the supernatant, and repeat three times. Next, transfer the treated algae into the prepared culture medium and place in the light incubator. The orthogonal experiment conditions of each group are controlled according to Table 2, the light dark ratio is 12 h : 12 h, and the sterile water is supplied quantitatively twice daily [25]. The concentration of chlorophyll a is measured 2 times per day at 9 pm and 3 pm. In the experiment, the chlorophyll a concentration is measured using a YSI 6600 multifunction water quality on-line measuring instrument [26].

2.3. Design of Orthogonal Experiment. After preculture and preservation of the algae species, each factor level is chosen according to the numerical water quality of the urban rivers and lakes of the Beijing water system in recent years, and we select and design a set of L_9 (3^4) experiments including four factors and three levels, as shown in Table 1.

Based on the nine experimental plans in the orthogonal factor level table L_9 (3^4), the experiment results are shown in Table 2.

Table 1: Factor level table for orthogonal experiment.

Number	Light intensity (lx)	Water temperature (°C)	TN (mg/L)	TP (mg/L)
1	6000	20	0.5	0.05
2	12000	28	2	0.1
3	18000	35	4	0.2

Table 2: Orthogonal experiment condition table for each group.

Number	Light intensity (lx)	Water temperature (°C)	TN (mg/L)	TP (mg/L)
1	6000	20	0.5	0.05
2	6000	28	2	0.2
3	6000	35	4	0.1
4	12000	20	2	0.1
5	12000	28	4	0.05
6	12000	35	0.5	0.2
7	18000	20	4	0.2
8	18000	28	0.5	0.1
9	18000	35	2	0.05

3. Results and Discussion

3.1. Experimental Analysis. The maximum biomass of algae (with chlorophyll a, unit g/L) and the maximum growth rate of algae (g/(L·d)) in the experimental results of the orthogonal experiment are shown in Table 3.

3.1.1. Analysis of the Maximum Algae Standing Crop (in the Form of Chlorophyll). Based on analysis of the orthogonal experimental data shown in Table 4, we can see that the range size of the four factors, in turn, is in the order water temperature > light > total phosphorus > total nitrogen, and the influence of algae growth and reproduction is in the order water temperature > light > total phosphorus > total nitrogen. The orthogonal experimental analysis is described as Figure 1, and it can be seen that the influence of the four factors on algae growth and reproduction remains consistent, and the growth of algae increases with the increase of each factor until a certain value when the algae growth begins to decline instead, which causes the maximum turmoil.

3.1.2. Analysis of the Maximum Daily Growth Rate of Algae (in the Form of Chlorophyll). The range analysis of the maximum daily growth rate of algae is shown in Table 5. We can see that the size order of the four factors is consistent with the maximum standing crop of algae, and the degree of influence on the algae growth and reproduction size is temperature > light > total phosphorus > total nitrogen. The intuitive analysis results of the orthogonal experiment are represented in Figure 2, which shows that the degrees of influence of the four factors on algae growth and reproduction are inconsistent with the largest stock on hand, but the influence of temperature is consistent; that is, an optimal growth temperature exists.

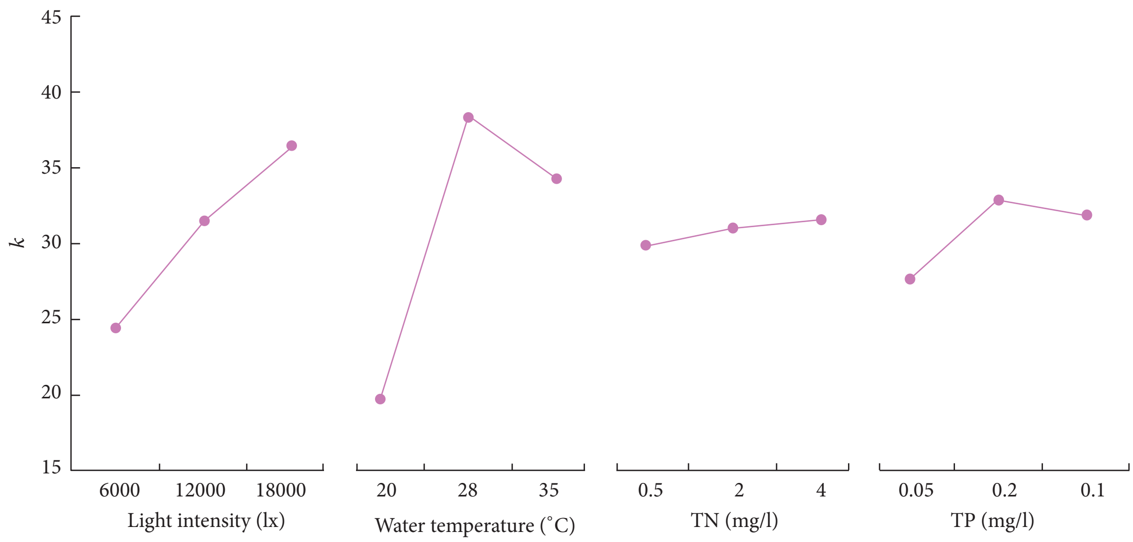

Figure 1: L_9 (3^4) orthogonal experiment: intuitive analysis diagram of algae with largest stock on hand.

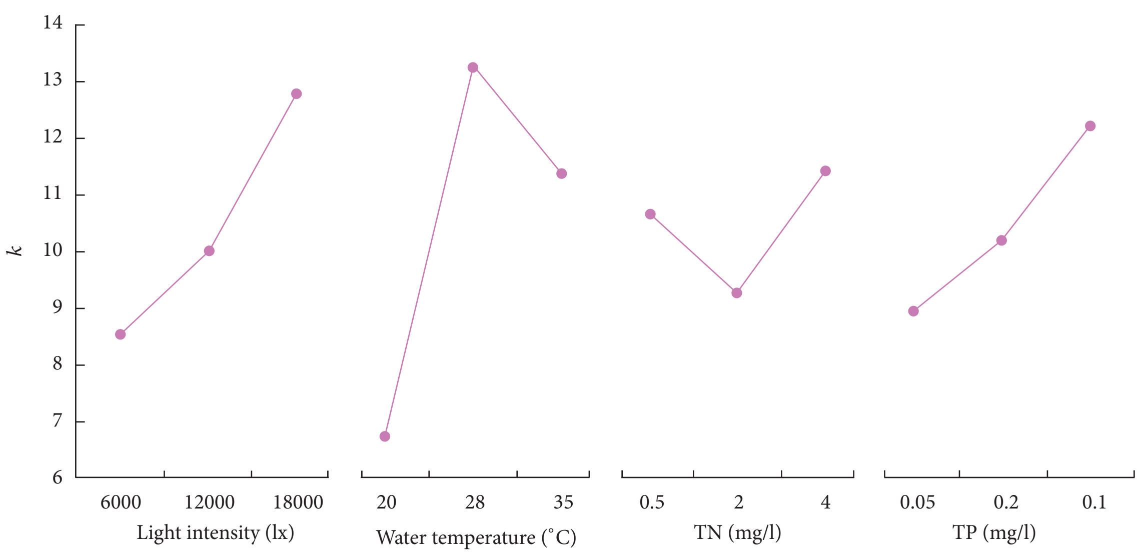

Figure 2: L_9 (3^4) orthogonal experiment intuitive analysis diagram of algae maximum daily growth rate.

Table 3: Data summary table of orthogonal experiment results.

	Light intensity (lx)	Water temperature (°C)	TN (mg)	TP (mg)	N/P ratio (mole ratio)	Number of experiment days	Experimental results chl-a/(μg/L)	Experimental results (μg/(L·d))
1	6000	20	0.5	0.05	22.14	12	9.3	3.5
2	6000	28	2	0.2	22.14	14	34.3	9.9
3	6000	35	4	0.1	88.57	13	29.8	12.2
4	12000	20	2	0.1	44.29	15	21.7	6.9
5	12000	28	4	0.05	177.14	15	36.7	12.3
6	12000	35	0.5	0.2	5.54	15	36.1	10.9
7	18000	20	4	0.2	44.29	14	28.2	9.8
8	18000	28	0.5	0.1	11.07	14	44.1	17.6
9	18000	35	2	0.05	88.57	14	37.1	11

Table 4: L_9 (3^4) orthogonal experiment range analysis of the maximum standing crop of algae.

Number	Light intensity (lx)	Water temperature (°C)	TN (mg/L)	TP (mg/L)	chl_a/(μg/L)
1	6000	20	0.5	0.05	9.3
2	6000	28	2	0.2	34.3
3	6000	35	4	0.1	29.8
4	12000	20	2	0.1	21.7
5	12000	28	4	0.05	36.7
6	12000	35	0.5	0.2	36.1
7	18000	20	4	0.2	28.2
8	18000	28	0.5	0.1	44.1
9	18000	35	2	0.05	37.1
$k1 = K1/3$	24.467	19.733	29.833	27.7	
$k2 = K2/3$	31.5	38.367	31.033	32.867	
$k3 = K3/3$	36.467	34.333	31.567	31.867	
R	12	18.634	1.734	5.167	

Table 5: L_9 (3^4) orthogonal experiment range analysis of the maximum daily growth rate of algae.

Number	Light intensity (lx)	Water temperature (°C)	TN (mg/L)	TP (mg/L)	chl_a/(μg/L)
1	6000	20	0.5	0.05	3.5
2	6000	28	2	0.2	9.9
3	6000	35	4	0.1	12.2
4	12000	20	2	0.1	6.9
5	12000	28	4	0.05	12.3
6	12000	35	0.5	0.2	10.9
7	18000	20	4	0.2	9.8
8	18000	28	0.5	0.1	17.6
9	18000	35	2	0.05	11
$k1 = K1/3$	8.533	6.733	10.667	8.933	
$k2 = K2/3$	10.033	13.267	9.267	10.2	
$k3 = K3/3$	12.8	11.367	11.433	12.233	
R	4.267	6.534	2.166	3.3	

When the light, temperature, total phosphorus, total nitrogen, and other conditions are sufficient, the chloroplast can convert inorganic phosphate and ADP to ATP, and the chloroplast absorbs light energy stored in the high-energy phosphate bonds of ATP to promote the growth of the algae. Under interaction with the optical system, the light energy is used to absorb and decompose water: O_2 is released, and ATP and NADPH are produced. The chemical reaction can be expressed as formula (1).

$$\begin{aligned} &2\mathrm{ADP} + 2P_i + 2\mathrm{NADP}^+ + \mathrm{H_2O} \longrightarrow \\ &2\mathrm{ATP} + \mathrm{O_2} + 2\mathrm{NADPH} + 2\mathrm{H}^+. \end{aligned} \tag{1}$$

When there is insufficient light, the chloroplast uses the chemical energy of NADPH and ATP produced by the photosynthesis reaction to reduce CO_2 to sugars and release the energy bond in high-energy phosphate for the decomposition of algae. This chemical reaction can be expressed by formula (2).

$$\begin{aligned} &6\mathrm{CO_2} + 18\mathrm{ATP} + 12\mathrm{NADPH} \longrightarrow \\ &\mathrm{C_6H_{12}O_6} + 18\mathrm{ADP} + 18P_i + 12\mathrm{NADP}^+. \end{aligned} \tag{2}$$

In fact, in the process of algae growth, reactions (1) and (2) occur in parallel at the same time, but during the early and late stage and under different conditions of bloom outbreaks the proportion of the reactions varies.

3.2. Evaluation Index Extraction of Water Eutrophication Based on Experiment. According to the orthogonal experiment results, in the process of water eutrophication, water temperature, illumination, total phosphorus, and total nitrogen are important factors in the bloom formation. There are also physical, chemical, and biological indicators that affect water status. Transparency is the most commonly used

Table 6: Principal component analysis results for secondary variables.

	Principal component factors							
Principal component	WT	SD	Dissolved oxygen	EC	pH	TP	TN	chl_a
1	−0.4528	0.4395	0.2273	0.4395	−0.3358	−0.1278	0.1454	−0.4546
2	−0.1856	−0.0259	0.0588	−0.0299	−0.2366	0.6671	−0.6744	−0.0683
3	−0.008	0.1417	−0.7894	0.0282	−0.5392	0.0468	0.1411	0.2078
4	0.4036	0.1324	0.1128	−0.0649	−0.033	0.6424	0.5694	−0.2544
5	−0.1772	−0.4980	−0.2033	0.7202	0.2869	0.2335	0.1428	0.0578
6	0.0185	−0.5936	0.3987	−0.0450	−0.6553	−0.0992	0.1713	0.1307

physical indicator. Total nitrogen and total phosphorus can correctly reflect the potential level of biological productivity of water and provide a better indicator for the judgment and control of water bloom. Some dominant populations of biological communities in the water body can be used as biological indicators. For a soft measurement system for eutrophication evaluation, the selection of the secondary variables, based on comprehensive analysis of the ecological conditions and the test index data of different rivers and lakes, can obtain more objective factors. For availability of indicators, WT, SD, Dissolved Oxygen, EC (Electrical conductivity), and pH are measured by YSI 6600 multifunction water quality on-line measuring instrument. The measurement method of TP is ammonium molybdate spectrophotometric method by GB 11893-89 in China. The measurement method of TN is potassium sulfate oxidation-ultraviolet spectrophotometry by GB 11894-89 in China. Light intensity is measured by weather station. COD is measured by potassium permanganate method which is also called potassium permanganate index. Light density is measured by SMARTAS813.

To determine the main factors influencing water bloom, the principal component analysis method is used to analyze the data, and the secondary variables of the evaluation model are determined. The contribution results from the principal component operation are shown in Table 6.

Table 6 shows that the contribution coefficients of TW, SD, EC, and chl_a are larger in the first principal component, while the contribution coefficients of TP and TN are larger in the second principal component. The main factors influencing bloom growth in the orthogonal experiment are weighed and combined with the biology of water eutrophication and information related to the COD description, identifying chl_a, TP, TN, COD, and SD as the main factors in eutrophication. Meanwhile, based on the results of principal component analysis, the weights of the five factors chl_a, TP, TN, COD, and SD in eutrophication assessment are, respectively, 0.27, 0.2, 0.2, 0.13, and 0.2.

3.3. The Water Eutrophication Application. The Bayesian method is used to evaluate the probability of event occurrence to describe the stochastic uncertainty and correlation of water quality variables. In the evaluation of water eutrophication, the sample space of random events is Ω; water samples $A \in \Omega$; B_i $(i = 1, 2, \ldots, s)$ indicate that the water eutrophication has s evaluation levels; $P(B_i)$ expresses that water is affiliated with the incidence of the level B_i; and $P(B_i) > 0$ is an ex ante estimate of the probability of S species level and is a prior probability, as there are five levels in the evaluation of eutrophication, so $P(B_i) = 0.2$. When $P(A) > 0$, the Bayesian formula is

$$P\left(\frac{B_i}{A_{kj}}\right) = \frac{P(B_i)\,P\left(A_{kj}/B_i\right)}{\sum_{j=1}^{s} P\left(B_j\right)P\left(A_{kj}/B_j\right)}, \quad (3)$$

where A_{kj} is the jth water quality index value of the kth water sample; $j = 1, 2, \ldots, m$; $k = 1, 2, \ldots, n$.

$P(B_i/A_{kj})$ reflects a new understanding of the possibility of the S species level in the presence of an index A and indicates the nutrition level probability in the process of lake eutrophication, so it is also called the posterior probability.

$P(A_{kj}/B_i)$ reflects the fact that the water quality indicators A indicate a certain level of eutrophication with the corresponding probability. The geometric probability method of distance representation used by $P(A_{kj}/B_i)$ calculates the reciprocal of the absolute value of the distance between the index value of a water quality sample and the eutrophication control standard value, as shown in formula (4).

$$P\left(\frac{A_{kj}}{B_i}\right) = \frac{\left(1/L_{ji}\right)}{\left(\sum_{i=1}^{s} 1/L_{ji}\right)}, \quad (4)$$

where $L_{ji} = |A_{kj} - B_{ij}| + 0.001$, and B_{ij} is the arithmetic mean of the upper and lower bounds of the ith eutrophication level of the indicator j.

The comprehensive value of water eutrophication assessment is based on the conditional probability-weighted calculation of the single index, as shown in formula (5).

$$P_i = \sum_{j=1}^{m} W_j P\left(\frac{B_i}{A_{kj}}\right). \quad (5)$$

Xihai, Qianhai, Houhai, and Yuyuantan of Beijing, four water quality-monitoring data locations, are chosen for evaluation by the Bayesian method. The specific information on the monitoring sites, time, and water quality data is shown in Table 7.

All levels of lakes were compared to maximize the corresponding probability: the corresponding level of the lake is the eutrophication status of the lake. The probability of the results evaluated using the Bayesian network is shown in Table 8.

We set evaluation result of expert opinion as the standard. Using the same calculation method to evaluate the water

Table 7: Water quality information at quality monitoring points.

	Year	Month	Date	Chl_a (mg/m^3)	TP (mg/m^3)	TN (mg/m^3)	COD (mg/L)	SD (/m)
Xihai	2012	6	6	17.74	80	2370	14.80	0.70
Xihai	2013	6	5	21.50	60	3140	10.40	0.64
Xihai	2013	7	3	7.17	30	1730	11.00	0.65
Xihai	2014	8	5	23.20	60	2620	12.70	0.40
Qianhai	2012	5	8	6.37	70	2740	13.50	1.50
Qianhai	2013	6	5	8.87	40	2340	10.90	1.00
Qianhai	2014	7	8	26.21	50	2110	9.40	0.80
Qianhai	2014	8	5	24.57	30	2310	8.60	0.40
Beihai	2013	6	5	23.38	80	1420	14.60	0.45
Beihai	2013	7	3	33.22	60	1040	15.10	0.62
Yuyuantan	2014	6	4	4.10	20	2200	35.10	0.40
Yuyuantan	2014	7	9	16.38	50	2940	29.10	0.38

Table 8: Bayesian evaluation results for water eutrophication.

	Year	Month	Date	I	II	III	IV	V	Evaluation level
Xihai	2012	6	6	0.1997	0.2102	0.1979	0.1923	0.1989	II
Xihai	2013	6	5	0.1874	0.2053	0.1923	0.1975	0.1991	II
Xihai	2013	7	3	0.219	0.2012	0.194	0.1971	0.1991	I
Xihai	2014	8	5	0.1914	0.2077	0.1992	0.1993	0.1996	II
Qianhai	2012	5	8	0.2252	0.2011	0.1892	0.2852	0.1972	IV
Qianhai	2013	6	5	0.2117	0.2034	0.1855	0.1942	0.1984	I
Qianhai	2014	7	8	0.1824	0.2009	0.1685	0.1967	0.1989	II
Qianhai	2014	8	5	0.1856	0.1924	0.1923	0.2005	0.1996	IV
Beihai	2013	6	5	0.1933	0.2024	0.2	0.1977	0.1994	II
Beihai	2013	7	3	0.1896	0.2056	0.1992	0.1932	0.199	II
Yuyuantan	2014	6	4	0.2508	0.2068	0.2	0.1998	0.1983	I
Yuyuantan	2014	7	9	0.2184	0.2263	0.2	0.1998	0.1991	II

quality of the 100 major lakes in our country and comparing the bias evaluation method with the single factor evaluation method of 90%, comprehensive evaluation method of 94%, and expert opinion set by national standards, we concluded that the evaluation result accuracy of the Bayesian method is 96%, and the overall trend of the evaluation results is consistent with expert opinion, which proves that this method is applicable to water eutrophication assessment.

4. Conclusions

The water eutrophication process is a complex mechanism involving many factors. To determine main factors, an orthogonal experiment was designed to analyze the key roles of illumination. Water temperature, total phosphorus, and total nitrogen in water eutrophication can all have large effect on algae growth by analyzing range value. These factors are determined as main factor. Moreover, we analyze the monitoring data of water quality to further determine main factors. By utilizing principal component analysis, we can extract the larger contribution of the principal components to the water eutrophication. Its results ultimately confirm the eutrophication evaluation indexes including chlorophyll a, total phosphorus, total nitrogen, COD, and transparency. Finally, in view of the uncertainty in the process of evaluation, the application of Bayesian theory in eutrophication assessment was examined. Compared with single factor evaluation method, comprehensive evaluation method, and expert opinion, Bayesian method was found to offer higher accuracy of 96% in eutrophication assessment.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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