Spatial and temporal variability of water productivity in the Syr Darya Basin, central Asia

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[1] Application of water productivity analysis can provide clues in the search for solutions to solve water management problems of central Asia. It is in this context that this paper provides an analysis of water productivity both spatially and temporally in the cotton and rice production areas of Syr Darya Basin of central Asia. The spatial analysis includes different farm types and basin segments, and the temporal analysis includes 3 hydrological years during 1999–2001. The analysis of temporal data showed that in water-deficient years, water productivity, both in terms of supply and evapotranspiration, is higher than the same in water-abundant years. The data also show that type and size of farms have an impact on water productivity in the case of both cotton and rice. This study concludes by suggesting strategies and options for enhancing the average water productivity both in the cotton- and rice-growing areas of the Syr Darya Basin.   *INDEX TERMS:* 1842 Hydrology: Irrigation; 1884 Hydrology: Water supply; 1719 History of Geophysics: Hydrology; *KEYWORDS:* irrigation, Syr Darya Basin, water productivity, central Asia

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1.   Introduction

[2] Irrigated agriculture is the major water use in central Asia, consuming almost 80–85% of the available water resources in the region. Water resources for irrigated agriculture in the region are provided by a vast irrigation network, spanning most of the arable lands in the Syr Darya Basin. For future sustainable development of the region it is crucial that every drop of water supplied to agriculture must be effectively used. The analysis of water productivity is becoming increasingly important worldwide in the light of population growth and increasing pressure on water resources. Such analysis can provide insights on means to improve overall agricultural water management. This study provides data on the spatial and temporal variation of water productivity in the Syr Darya Basin for a better understanding of how effectively water is used in irrigated agriculture.

2.   General Background

[3] The Syr Darya Basin covers an area of 444,000 km^2 and is home to ~18 million people, with an overall population density of 19 people per km^2. The Syr Darya River originates in the Tien Shan Mountains and flows through the upstream countries of Kyrgyzstan and Tajikistan, through Uzbekistan and Kazakhstan, before flowing into the Aral Sea (Figure 1). The total length of the Syr Darya is ~2500 km. The average temperature in the basin is 14.2°C, ranging from −15° to 8°C in winter and 18° to 38°C in

summer. The annual precipitation ranges from 60 mm at Kzylorda (tail reach) to 502 mm at Djalalabad (upper reach). Evaporation ranges from 1150 to 1420 mm within the basin.

[4] At the beginning of the 1960s, the former Soviet Union (FSU) launched efforts to increase cotton production in central Asia. Billions of cubic meters of water were diverted to irrigate cotton and paddy fields through a massive infrastructure development program. While such water diversion has helped to increase the command area from 5 million hectares (mha) in the 1950s to 8 mha in the 1990s, it has also caused a drastic change in the natural flow regime and ecosystems in the area. The diversions of water for agriculture from the Syr Darya are almost equal to its total annual inflow, and the drainage flows into the Aral Sea have declined far below the environmentally acceptable limits. In the absence of the scope for additional water supplies from an interbasin transfer, improved water management and higher productivity of irrigation water are the only options available for meeting increasing food and livelihood requirements of the region.

3.   Research Methods and Data Collection

[5] Data for the water productivity analysis were derived from the project "Adoption of Best Practices for Water Conservation in the Syr Darya and the Amu-Darya River Basins of Central Asia" (conducted as a joint project of IWMI and Scientific Information Center of Interstate Coordination Water Commission (SIC-ICWC), this project is the logical continuation of the Water Saving Competition, funded by the World Bank and Global Environmental
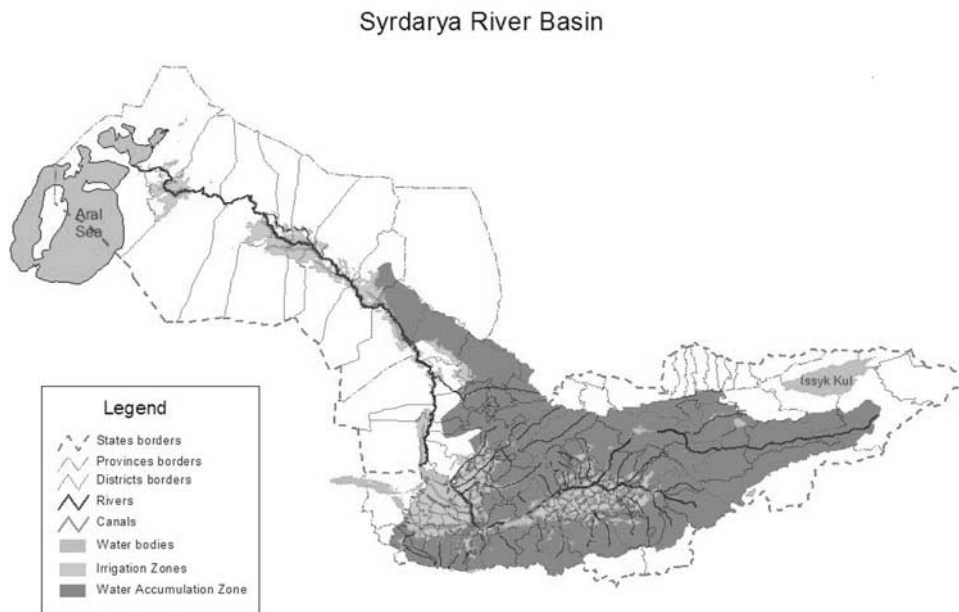
Figure 1. Map of irrigated areas in the Syr Darya Basin (Source: *Abdullaev et al.* [2003]). See color version of this figure in the HTML.

Facility (GEF)). This was the second step of the "Participation in Water Conservation" project, conducted in central Asia during the 1999–2000 period [*Khorst et al.*, 2002]. Eleven water management organizations (WMOs), seven water users associations (WUAs), 18 collective-cooperative farms (CCFs) and 25 private peasant farms (PPFs), located in the head, middle, and lower reaches of Syr Darya Basin participated in the project. This sample may not be representative of the entire basin, but nevertheless, it can provide important insights into water productivity.

[6] The data collection in the "Best Practices" project was carried out by trained field observers for sample fields (one field observer for each pilot plot), by farm monitors for agricultural enterprises (one for each CCF or PPF), and by district observers for water management organizations (one monitor for each WMO).

[7] Farmers, irrigation engineers, and agronomists were hired and trained as observers and were paid for data collection. The week-long workshops and field trainings were carried out by the Scientific Information Center of the Interstate Commission on Water Coordination (SIC-ICWC) and the International Water Management Institute's Central Asian and Caucasus Subregional Office (IWMI-CAC) staff for field observers, farm monitors, and district observers. To coordinate and ensure quality of data for each province, one technical person was appointed as an oblast monitor. A total of six oblast monitors was hired for the project area.

[8] During measurement, incorrect installation and inaccurate reading and recording were problems. This was either due to a lack of training or lack of incentive to do the job. Appropriate steps were undertaken to overcome these problems. The quality of the data recording was regularly checked in situ. Water measurements were performed by the use of measurement devices installed at the inlet and outlet of each sample field, farm, and irrigation system. The observers recorded the readings and monitored the irrigation schedule accordingly. During irrigation the observers took hourly records of water depth or discharge. The observers and monitors made the following observations in the fields, farms and WMOs: (1) For monitoring of crop development (phenology of crops), planting dates, type of seeds, cultivations, crop development stages, stresses in the crop development, diseases, harvesting, and crop yield determination were observed. (2) For water measuring, presowing and postsowing irrigations, inflow-outflow discharges (hourly), drainage inflow, soil moisture check 3 days prior to irrigation and 3 days after irrigation, and groundwater level (daily) were observed. (3) For agroeconomic monitoring, crop growth and associated expenses; agricultural practices, applied with dates, amounts, and expenses for such practices; water conservation practices and expenses for application; and fertilizer, pesticide, and herbicide applied, with dates and expenses were observed. (4) For monitoring of salt balance, salt content of irrigation, drainage and groundwater, and soil salt content were observed.

[9] In this study, water productivity analysis was carried out for 3 years (1999, 2000, and 2001) and for two levels of water use (CCFs and PPFs). This was done for three reaches of basin: upper, middle, and tail. Only water productivity of main crops, cotton (upper and middle reaches) and rice (tail), was analyzed.

4. Results

[10] Water productivity (WP) analysis combines physical accounting of water with yield or economic output to give an indication of how much value is being obtained from the use of water [*Molden*, 1997]. For this analysis, physical water productivity was calculated by

$$WP = Output/Q, \qquad (1)$$

where WP is the productivity of water (in kg/m^3), Output is the mass of crop yield (in kg), and Q is water resources
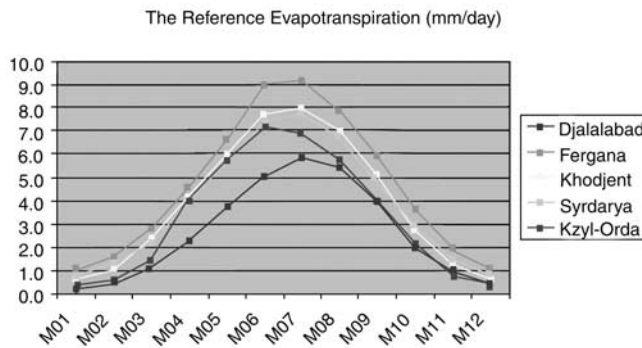
The Reference Evapotranspiration (mm/day)

Figure 2. Reference evapotranspiration for different (head, middle, and tail) reaches of Syr Darya Basin. See color version of this figure in the HTML.

supplied or depleted (m^3). In this study, two types of water productivity were calculated: physical water productivity of total supplied irrigation water (WP_{supply}, kg/m^3) and physical productivity per unit of evapotranspiration (WP_{ET}, kg/m^3).

4.1. Productivity of Total Surface Water Supplied to a Farm (WP_{supply})

[11] For this analysis the supply is the measured total inflow of water into a unit. A problem then is knowing how much of the supply goes to cotton or rice versus other crops. In central Asia the share of cotton in the cropping pattern varies from 95.9 (south Kazakhstan province) to 40.4% (Osh province). The highest share of water supply in the vegetation season (April–September) is mainly for cotton irrigation in the cotton-growing area. Therefore we assume that all water is supplied for cotton in the vegetation season in cotton-growing areas. Similarly, we assume that all water supplied to units in rice-growing areas is for rice. We are confident from our field observations that these are good assumptions.

4.2. Productivity of Evapotranspiration (WP_{ET})

[12] In this study we have used subscript ET to WP to mean the unit productivity per unit of water depleted from the basin by the crop production process. Increases in WP_{ET} will result in overall basin-wide water productivity increases. In contrast, increases in WP_{supply} do not necessarily constitute overall basin productivity gains because return flows may be reused for higher-valued uses.

[13] In order to assess the productivity of ET in equation (1), Q equals ET_{pot}, the potential rate of evapotranspiration for a non-water-stress crop. For simplicity, we assumed that potential ET is close to the actual ET. This assumption is reasonable as most farmers would not like to lose yields by stressing their crops. For different crops, ET_{pot} was calculated using the Food and Agricultural Organization method [Allen et al., 1998], given by the following equation:

$$ET_{pot} = K_c ET_{ref}, \qquad (2)$$

where ET_{ref} is reference evapotranspiration determined from Figure 2 and K_c is crop coefficient (crop coefficients for cotton and rice for different reaches of Syr Darya Basin

were obtained from *Sredazgiprovodkhlopok Research Institute* [1970]).

[14] The reference evapotranspiration (ET_{ref}) in Figure 2 was calculated for five meteostations of the Syr Darya Basin on the basis of the average long range meteorological data [*Interstate Commission on Water Coordination* (*ICWC*), 1997].

4.3. Temporal and Spatial Analysis of Water Productivity in Syr Darya Basin

4.3.1. Spatial Water Productivity Analysis

[15] The results of the analysis are shown in Table 1. In our data set the average size of CCFs is 1558.9 ha and PPFs is 128.2 ha. The absolute highest WP_{supply} (0.60 kg/m^3) and WP_{ET} (0.75 kg/m^3) for cotton-growing areas were observed for upper reach PPFs (Figure 3). The lowest WP_{supply} (0.31 kg/m^3) and WP_{ET} (0.40 kg/m^3) were observed for CCFs in the upper reach of the basin (Table 1).

[16] For the cotton-growing area, water productivity of supplied water (WP_{supply}) is lower than the potential evapotranspiration productivity (WP_{ET}). The major reason for this is the relatively high water supply to crops, exceeding the amount for exceeds crop evaporative water requirements in spite of the fact that rain also contributes a part of overall supply. Cotton yields are higher in PPFs than CCFs by 0.5–1.0 tons/ha, leading to higher values of water productivity.

[17] The average WP_{supply} for cotton-growing areas (0.37 kg/m^3) is quite low compared to other crops [*Molden et al.*, 1998]. It has been difficult to raise cotton yields from the 2.5 to 3.5 tons per hectare mark, but results indicate that there is scope to reduce supply to cotton areas and increase water productivity per unit supply.

[18] The highest WP_{supply} (0.26 kg/m^3) and WP_{ET} (0.58 kg/m^3) for rice were observed for PPFs. The lowest water WP_{supply} (0.15 kg/m^3) and WP_{ET} (0.33 kg/m^3) were also observed for PPFs. In rice areas, WP_{supply} is much lower than WP_{ET}. In the tail end of Syr Darya Basin, application rates to the rice crop are very high, and rice yields are also quite low at 2.2 tons/ha, both factors leading to very low values of water productivity.

[19] The major outcomes of spatial analysis of water productivities are the following: (1) Both WP_{supply} and W_{ETpot} are higher in the private farming units of cotton-growing areas. The difference in water productivity between reaches is not notable. (2) Differences between WP_{supply} and WP_{ET} indicate that supplies could be reduced. (3) There is almost 2 times difference between highest and lowest water productivities (both for WP_{supply} and W_{ETpot}). This indicates that there is high potential to increase average values of water productivity within the basin.

4.3.2. Temporal Water Productivity Analysis

[20] Temporal water productivity analysis was done for years 1999, 2000, and 2001. The years 1999 and 2001 were years of normal water availability, while in 2000, there were water shortages. In 2001, the water supply rates were 13–15% higher than in 2000 for all types of farms in cotton-growing areas.

[21] The highest WP_{supply} and WP_{ET} for cotton were 0.60 kg/m^3 and 0.75 kg/m^3, respectively, and they were observed in 2000 (the water shortage year). The lowest mean values for WP_{supply} and WP_{ETpot} for cotton-growing areas

Table 1. Farm Level Water Productivity for Cotton and Rice in the Syr Darya Basin (1999–2001)

Reach	Type of Unit[a]	Year	Number of Monitored Farms	Average Size, ha	Average Water Supply Rate, m^3/ha	ET_{pot}, m^3/ha	WP_{supply}, kg/m^3	WP_{Etpot}, kg/ET
				Cotton				
Upper	CCF	1999	4	156.3	6950	5120	0.36	0.49
Upper	CCF	2000	4	156.3	6950	5124	0.36	0.49
Upper	CCF	2001	4	156.3	8000	6245	0.31	0.4
Upper	PPF	1999	8	13.06	8200	5120	0.38	0.61
Upper	PPF	2000	8	13.06	6400	5124	0.6	0.75
Upper	PPF	2001	8	13.06	7900	6245	0.43	0.54
Middle	CCF	1999	10	2254.6	7200	6540	0.43	0.47
Middle	CCF	2000	10	2254.6	8100	6700	0.45	0.54
Middle	CCF	2001	10	2254.6	7400	6870	0.45	0.48
Middle	PPF	1999	12	78.14	6900	6540	0.49	0.52
Middle	PPF	2000	12	78.14	8100	6700	0.57	0.69
Middle	PPF	2001	12	78.14	7000	6870	0.5	0.51
				Rice				
Tail	CCF	1999	4	2254.6	18300	8750	0.25	0.52
Tail	CCF	2000	4	2254.6	20000	8800	0.24	0.55
Tail	CCF	2001	4	2254.6	24000	8900	0.18	0.49
Tail	PPF	1999	4	293.5	19000	8750	0.15	0.33
Tail	PPF	2000	4	293.5	19500	8800	0.26	0.58
Tail	PPF	2001	4	293.5	21400	8900	0.16	0.38

[a]CCF, collective-cooperative farm; PPF, private peasant farm.

were observed in 2001 (normal rainfall year), at 0.31 kg/m^3 and 0.40 kg/m^3, respectively. The highest water productivities (WP_{supply} and WP_{ET}) for both CCFs and PPFs were observed in 2000. Similarly, the highest rice WP_{supply} and WP_{ET} (0.26 kg/m^3, 0.58 kg/m^3) were also observed in 2000. The highest WP_{ET} (0.75 kg/m^3) and the lowest WP_{ET} (0.40 kg/m^3) for cotton were observed in the upper reaches in 2000 and 2001, respectively.
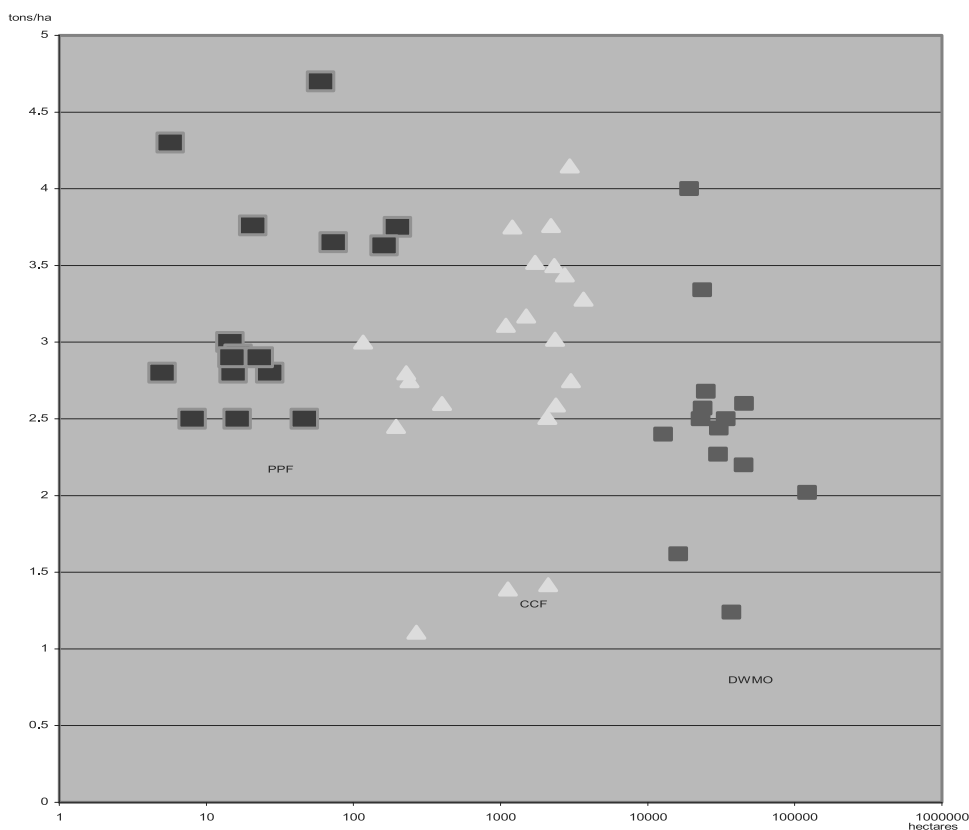

Figure 3. Cotton yields for different water management and use units in Syr Darya Basin (source: *Murray-Rust et al.* [2003]). See color version of this figure in the HTML.

[22] An analysis of the spread of water productivity values within years is instructive. In 1999, the highest cotton WP_{supply} was monitored in the middle reach (0.49 kg/m^3), while the lowest (0.36 kg/m^3) was observed in the upper reach, a difference of 0.13 kg/m^3. The highest and lowest WP_{supply} in 2000 (0.60 and 0.36 kg/m^3) were monitored in the upper reach, a difference of 0.24 kg/m^3, almost double that of 2000. In water shortage years the difference between the best and least water productivity is high in spite of an overall average increase in water productivity.

[23] The difference between the WP_{supply} and WP_{ET} for maximum mean values in 1999 was 0.23 kg/m^3, in 2000 was 0.11 kg/m^3, and in 2001 was 0.13 kg/m^3. These comparisons indicate that in dry years the lowest difference between WP_{supply} and WP_{ET} can be achieved because supplies come closer to matching the evapotranspiration requirements.

[24] In rice-growing areas the maximum of WP_{supply} and WP_{ET} was observed in 2001 (0.26 and 0.58 kg/m^3, respectively), and the lowest water productivities were observed in 1999 (0.15 and 0.33 kg/m^3). Water productivities for rice were not the highest during the dry year. The temporal analysis of water productivities showed the following trends: (1) The highest means of both WP_{supply} and WP_{ET} for cotton was achieved in the year with less water availability. (2) In dry years the difference between water supply and potential ET productivities is less than in normal water availability years.

5. Discussion

[25] Water productivity is a function of crop yields and water management practices. As such, there are many means of increasing water productivity as outlined by *Molden et al.* [2003], ranging from field- to basin-level practices. Field practices such as tillage, soil fertility, and varieties influence water productivities [*Hussain et al.*, 2003]. Less water through changes in water management practices influence water productivity. Additionally, there are important interactions between water management and farm practices. More reliable supplies can lead to less risk for farmers and more investments in yield, enhancing agronomic practices. Water management practices that lessen salinity hazards can be important in keeping yield levels high. Irrigation systems and basin water allocation systems influence how farmers manage water. Policies providing incentives for higher productivities can be instrumental in increasing water productivities. This analysis gives key indications that all of these are at play within the Syr Darya Basin.

[26] The study provides a demonstration of how water productivity analysis can be useful in pointing to improved practices. Because best practice sites where chosen, we cannot extrapolate results to the rest of the basin. Nevertheless, the field results provide important information on water productivity in the basin.

[27] The analysis shows that even among best practices, there is considerable variation in water productivity. This indicates that there is scope to increase average water productivity in the basin by closing the gap between low and high values of water productivity.

[28] The analysis provides evidence that nonwater influences make a big difference in yields. After the collapse of centralized planning economy under Soviet rule, in upper (Kyrgyzstan) and the tail reaches of the basin (Kazakhstan), availability of inputs are limited. Policies influencing agricultural practices influence water productivity. This study showed higher values of water productivity obtained in privately owned than collectively owned farms.

[29] On-farm water management makes a difference. The difference in water productivity per unit of supply and ET in normal and dry years is striking. This gives evidence that with more care about water and other inputs, better water productivity values can be achieved. This leads to the question of which incentives can be put in place such that the same care of water is provided in the dry years.

[30] Managing water within irrigation systems and within the basin influences water productivity. Low values of water productivity at the tail end, especially among rice farmers, show difficulties in uniformly and fairly distributing water, thus lowering water productivity values. In the dry years, even though higher values of water productivity were obtained, the gap between lowest and highest values of water productivity was greatest, indicating problems of uniform water distribution.

[31] On the basis of this initial screening, some steps can be recommended. The first is to better understand the constraints of higher water productivity. Knowing which factors, for example, fertility, water management practices, salinity, or others factors, will point to actions to remove these constraints. A second step is to learn from good practices where farmers and water managers exhibit high levels of water productivity, as is being done by the best practice project described in this document. A third action is to split the region into areas of similar water management regimes, hydronomic zones [*Molden et al.*, 2001], or similar farm types (private or collective, large or small) to better understand how these can be improved in the central Asian context. This knowledge will help design water management practices, incentives and policies that can improve water productivity.

6. Conclusions

[32] In the Syr Darya Basin, like many basins of the world, improving water productivity is important to maintain or increase production levels in the face of increasing competition for limited water supplies. In the Syr Darya it is likely that agriculture will have to release water to urban and environmental uses. With less water, agriculture has to do more with less water to sustain and improve livelihoods and to improve the overall economy.

[33] This analysis demonstrates that there is considerable scope for water productivity increases within the Syr Darya Basin and provides some indication on how these increases can be achieved. The analysis provides an important demonstration of how water productivity analysis can be done. Then it shows how the results can be used to provide indications of how water productivity can be increased.

[34] The analysis showed that in dry years, water productivity levels are higher than wet years, showing that farmers and water managers are capable of achieving higher levels of productivity. It shows that there are spatial differences that are a function of basin and irrigation system level practices. There are considerable differences between farm policies and practices. For example, private farms exhibit higher levels of water productivity than collective farms.

From the sample chosen, we cannot immediately extrapolate to the entire basin, but the results indicate where and how water productivity improvements can be made. It indicates that further analysis and actions are warranted to increase water productivity.

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