Visual_HEA: Habitat Equivalency Analysis software to calculate compensatory restoration following natural resource injury

Kevin E. KOHLER* **and Richard E. DODGE**

National Coral Reef Institute, Nova Southeastern University Oceanographic Center, 8000 North Ocean Drive, Dania Beach, FL 33004, USA
*Corresponding author: K.E. Kohler
Tel.: 954-262-3641, Fax: 954-262-4158, e-mail: kevin@nova.edu

Abstract Habitat Equivalency Analysis (HEA) is a means to determine the amount of compensatory restoration required to provide services that are equivalent to the interim loss of natural resource services following an injury. HEA includes a discounting procedure to account for asset valuation in that the total asset value is equal to the discounted value of the future stream of all services from the natural resource or the compensatory resource. Discounting is used to include the relative valuation of loss and gain of ecological services of the resources over time. Visual_HEA is a computer program developed to calculate the amount of compensatory resource services that would be required to match those lost following an injury to natural resources. The program accepts input of parameters necessary to determine long-term service loss from the injury and long-term service gain from the desired compensatory restoration action. HEA results are highly dependent upon assumptions, and consequently it is useful to examine sensitivity of results to a range of parameter values. Visual_HEA offers an intuitive graphical interface that allows the user to input or modify input parameters and hence quickly create or alter the lost and gain service level shape functions. The ability to calculate results of many scenarios allows ready comparisons that may assist in determination of the most appropriate compensatory action.

Keywords habitat equivalency analysis, ecosystem restoration, ecosystem models, cost-benefit analysis, software

Introduction

Because of pervasive degradation of coral reefs globally as a result of both natural and anthropogenic causes, there has been a burgeoning interest in methods that could restore reefs. One of the ways that has been used in the United States has been to attempt to determine the nature and degree to which a restoration project might provide adequate replacement for an injured resource via Habitat Equivalency Analysis (Dunford et al. 2004; Milon and Dodge 2001; Mazzotta et al. 1994; Unsworth and Bishop 1994)

In overview, Habitat Equivalency Analysis (HEA) is a means to determine the amount of compensatory restoration required to provide services that are equivalent to the interim loss of natural resource services following an injury. HEA uses a discounting procedure to account for asset valuation in that the total asset value is equal to the discounted value of the future stream of all services from the natural resource or the compensatory resource. Discounting is used to determine the relative valuation of the loss and gain of ecological services of the resources over time relative to time of analysis. Therefore, the HEA approach is particularly well suited for analysis because it can be used to quantify the amount of loss and gain of resources and services over time.

We have developed a computer program, Visual_HEA, that accepts input of user-defined parameters representing HEA assumptions related to loss of services from a natural resources injury and gain of services from a desired compensatory action. Visual_HEA illustrates many of the parameters graphically and calculates the amount of compensation required to offset the loss of services. It is the purpose of this paper to describe the features of this program. The reader should refer to the Habitat Equivalency Analysis references given above for more information on the HEA procedure. Visual_HEA does not provide exhaustive options for all HEA contingencies, yet many of the more common attributes commonly required by users have been incorporated, and therefore should be useful to a wide range potential user applications. Program restrictions are identified in this paper. Future releases of the software will hopefully address some of these restrictions.

HEA Methodology

The following is an overview of the HEA methodology used in the Visual_HEA program. The same or similar naming conventions as found in NOAA (1995, 2000) are employed. In order to meet length restrictions of the Proceedings, the reader is directed to these references for a more detailed discussion of input parameters and methodology.

To perform an HEA analysis, a variety of input parameters are required. Each of these quantities is described below.

Relative value of pre-injury services and compensatory (at equilibrium) services. These parameters indicate the value per area of services provided both at the injury site (pre-injury) and at the restoration site. In this formulation of the Visual_HEA program, the relative values are held constant throughout the analysis.

Baseline levels of services. These percentage values indicate the level of services being provided by the injury site prior to injury and the level of services provided by the restoration site prior to any restorative action. That is, in the case of the injury site, the baseline represents the level of services that would have been provided by the site had injury not occurred. For example, the baseline level of services of a habitat prior to injury might be considered to be 100% (full services) or at some lower value depending upon the condition of the habitat. The services level provided by the restoration site immediately prior to restoration action might be 0% (no services) or might be some higher value again depending upon the condition of that habitat. For the purposes of the current configuration of Visual_HEA, these baseline levels are considered time-invariant throughout the time of analysis.

Discount rate. This parameter incorporates the assumption that services provided sooner are more highly valued than those provided later. Since service losses and gains occur at different times, they must be adjusted in order to be directly compared. This adjustment is accomplished using a discount factor which decreases the value of future services and increases the value of past services in order to reflect how much the public values future (or past) service benefits today. This discount rate is specified as a percentage rate per time unit.

Year of claim. This is the year in which the claim is being made. The "claim" could be in a legal sense or, more generally, simply as an anchor point in time. The HEA calculations use the claim year as the reference point in calculating discounted service levels, i.e., the discount level at this year is 1.0.

Service loss parameters from the injury. This includes the size of the injury area and the time history of the loss of services at the injury site, *i.e.* the duration and level of service loss from time of injury through natural or assisted recovery, if any.

Service gain parameters from the compensatory action (restoration). This includes the time history of service levels of the compensatory action, *i.e.*, the duration and levels of services gained from initiation of the compensatory action throughout its persistence.

HEA results are highly dependent upon the input parameters described above. It is therefore often useful to calculate results using a range of parameter values. Visual_HEA software facilitates multiple runs by offering a graphical user interface where the user can easily modify input parameters and the time structure of the service loss and gain shape functions. The ability to formulate and determine the results of many scenarios can provide an indication of the sensitivity of the required compensatory action scale to various input parameters.

The relevant variables required for performing HEA analysis are shown in Table 1.

Time variables	
$t = 0$	Time when injury occurs
$t = B$	Time when injured area recovers to baseline levels
$t = C$	Time when the claim is presented
$t = I$	Time when the habitat project begins to provide services
$t = M$	Time when the habitat replacement project reaches full maturity
$t = L$	Time when the habitat replacement stops yielding services
Other variables	
V_j	value per area-time of services provided by injured habitat
V_p	value per area-time of services provided by replacement habitat
x_t^j	level of services provided by injured habitat at end of time *t*
b^j	the pre-injury baseline level of services per area of injured habitat
x_t^p	level of services provided by replacement habitat at end of time *t*
b^p	initial level of services per area of replacement habitat
ρ_t	discount factor, where $\rho_t = 1/(1+r)^{(t-C)}$, r=discount rate per time unit
J	number of injured area units
P	size of compensatory replacement project
Calculated quantities	
$(b^j - x_t^j)$	Extent of injury at time t
$(x_t^p - b^p)$	Increment in services provided by replacement project
$(b^j - x_t^j)/b^j$	percent reduction in services per area for injured area, relative to the injury site baseline level of services
$(x_t^p - b^p)/b^j$	percent increase in services per area for replacement site, relative to the injury site baseline level of services

Table 1. Parameters used in Habitat Equivalency Analysis

The ultimate goal of Habitat Equivalency Analysis is to solve for the size of the compensatory replacement project P. To accomplish this, the sum of the present value of services lost as a result of the injury is set equal to the present value of the services provided by the replacement project:

$$\left(\sum_{t=0}^{B} V_j \cdot \rho_t \cdot \left(b^j - x_t^j\right)/b^j\right) \cdot J = \left(\sum_{t=I}^{L} V_p \cdot \rho_t \cdot \left(x_t^p - b^p\right)/b^j\right) \cdot P \qquad (1)$$

It is useful to define two quantities, λ_t and γ_t which represent the discounted effective area lost and the discounted effective service gain per unit area, respectively. They are given by:

$$\lambda_t = \rho_t \cdot J \cdot \left(b^j - x_t^j\right)/b^j \qquad (2)$$

$$\gamma_t = \rho_t \cdot \left(x_t^p - b^p\right)/b^j \qquad (3)$$

The units of λ_t are in area units, while γ_t is non-dimensional. If V_j and V_p are considered time invariant, P can then be solved for as:

$$P = \frac{V_j}{V_p} \cdot \frac{\left(\sum_{t=0}^{B} \rho_t \cdot \left(b^j - x_t^j\right)/b^j\right) * J}{\sum_{t=I}^{L} \rho_t \cdot \left(x_t^p - b^p\right)/b^j} = \frac{V_j}{V_p} \cdot \frac{\sum_{t=0}^{B} \lambda_t}{\sum_{t=I}^{L} \gamma_t} \qquad (4)$$

There are two special cases to be addressed: 1) when the service levels at the injury site never attain their pre-injury baseline levels and 2) when there is no time limit when the restoration habitat stops yielding services. Mathematically, this is equivalent to both *B* and *L* approaching infinity. For these cases, Visual_HEA gives the user the option of having the service levels of either or both of the injury site and restoration site remain in perpetuity. This requires adding on the amount of services gained or lost from the time of maturity (*M*) to infinity. In the case where V_j and V_p are time-dependent, the user has to run the analysis far enough such that the multiplicative discount factor renders additional terms insignificant. However, in the case where V_j and V_p are considered time invariant, the additional term can be calculated as follows. (The derivation given below is for services lost at the injury site. A similar technique can be used for the restoration site).

Define *S´* to be the additional term to be calculated, i.e. the contribution to the sum of services lost due to perpetuity.

$$S' = V_j \cdot J \cdot \sum_{m=M+1}^{\infty} \left(\frac{(b^j - x_M^j)}{(1+r)^{m-c}}\right) \qquad (5)$$

Define the term $S_M = V_j \cdot J \cdot \dfrac{(b^j - x_M^j)}{(1+r)^{M-c}}$ (6)

This term is the contribution to the discounted effective area at time $t = M$.

Grouping additional time-independent terms in (5) yields:

$$S' = V_j \cdot J \cdot \frac{(b^j - x^j{}_M)}{(1+r)^{M-c}} \sum_{m=1}^{\infty} \left(\frac{1}{(1+r)^m}\right) = S_M \sum_{m=1}^{\infty} \alpha^m$$

where $\alpha = \dfrac{1}{1+r}$. (7)

Dividing each side of (7) by α yields:

$$\frac{S'}{\alpha} = S_M \sum_{m=0}^{\infty} \alpha^m \qquad (8)$$

Subtracting (7) from (8) yields:

$$S'(\frac{1}{\alpha} - 1) = S_M \text{ or } S' = \frac{S_M}{r} \qquad (9)$$

Thus, for time-independent values of V_j and V_p, the contribution due to perpetuity can be exactly determined. This is the form used in the current version of Visual_HEA.

Case Study to Illustrate Use of Visual_HEA: Calculating the Amount of Nearshore Compensatory Action for Beach Renourishment Injury to a Coral Reef Community

A better understanding of the parameterization and operation of Visual_HEA can be facilitated by discussion of a relatively simple case study (although more complex cases are possible). This case study is a plan for the renourishment of beaches that anticipates covering 10.1 acres (4.1 ha) of nearshore hardground coral reef community habitat with sand used for beach renourishment. Assume local government proposed to provide mitigation (compensatory action) in the form of limestone boulders as habitat in order to compensate for the loss of the 10.1 nearshore reef habitat acres (4.1 ha). An HEA was performed to calculate amount of the compensatory action that would be needed. In order to complete the HEA, various assumptions were made about the loss of services of the hardground acres to be covered and the gain of services from the compensatory action, the discount rate, and the start times and amounts of lost and gained services of the injury and compensatory restoration.

Assumptions included the following:

General program parameters:

Relative value of lost and gained services

It was assumed that the ratio of the value of services of the injury area (pre-injury) versus for the compensatory action (after it reaches full services) was 1.0. This assumption means that the value of services per acre of the nearshore hardbottom community before injury was equal to the value of services per acre provided by the boulders at the restoration site. This doesn't have to be the case for all formulations. One might imagine compensatory actions which would only eventually provide half the services of the pre-injury baseline. In such a case, the appropriate ratio would be 2.0.

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Discount rate

The historical value of 3% was used.

Specific program parameters:

Extent of injury and loss of services of the nearshore reef hardground

- The nearshore injury begins in 2003
- 20% of the 10.1 acres (4.1 ha) was lost immediately when sand was placed in 2003
- 100% of the 10.1 acres (4.1 ha) was lost 3 years later in 2006
- 100% loss of the 10.1 acres (4.1 ha) continues in perpetuity (i.e., the habitat remains sand covered forever)

It was assumed that the initial placement of the renourishment sand on the beach in 2003 would cover only about 20% of the associated nearshore hardbottom. As the beach sand equilibrated to the natural wave climate, it was assumed the coverage of the hardbottom would extend to 100% of the 10.1 acres (4.1 ha) after 3 years in 2006. It was conservatively estimated that the 10.1 acres (4.1 ha) would remain covered ad infinitum. (It is possible that the nearshore acreage would be uncovered by beach erosion within decades. Such an eventuality could be factored into the HEA through appropriate node placement. For example 100% loss might end after 20 years in 2026 whereupon natural recovery might begin).

Services gained by the compensatory action (mitigation boulders)

- The compensatory action (mitigation) also begins at the same time in 2003.
- 10% of services gained upon transplantation of stony corals (from the area to be injured) older than 15 years onto boulders in 2003. The boulders are assumed to be transplanted immediately and so the 10% services gain is also immediate.
- 100% full services reached after 15 years in 2018
- 100% full services continues in perpetuity.

It was assumed that while the mitigation boulders will recover to 100% full services in 50 years naturally, they will recover to 100% full services in less time (15 years) by transplanting corals onto them. 15 years was chosen because all corals greater than 15 years old were to be removed from the area slated for injury. These would be used for transplantation. By transplanting corals, the mitigation boulders will begin recovery not at 0% of full services, but at some higher value. A level of 10% immediate gain of services was assigned. (This analysis assumed that the boulders would reach services of 100% and that these services would persist forever. Other assumptions might have included that boulder services would only reach some level less than full services or that the boulders would only persist for a finite time period, e.g., bioerosion might be invoked to destroy the boulders in 50 years at 2053, hence eliminate any services provided beyond that time.)

HEA Program Operation

The HEA program interface consists of a single main form. To perform an analysis, the following initial information must be entered (Table 2). Values used in the case study are provided in the rightmost column.

Parameter: Explanation	Case study parameter value
Site name**:** name of analysis site, analysis, etc	Beach Renourishment
Present year**:** year of analysis. This gives the reference time from which discounted service losses and gains are calculated.	2003
Number of injured area units**:** size of injury site in spatial units	10.1
Ratio of injured/restored service values: relative value of lost versus gained services per time-area unit	1.0
Discount rate (%) per time unit: amount of discounting to reflect the relative value of present versus future service levels	3%
Pre-injury service level: level of services provided by the injured area prior to injury	100%
Initial compensatory service level: level of services provided by the compensatory action area at the onset of the compensatory action	10%
Area and time units	acres, years
Service loss display years: time span of service loss to be displayed on the graphs (and to have as discrete calculation results in the printouts	2002-2020
Service gain display years: time span of service gain to be displayed on the graphs (and to have as discrete calculation results in the printouts	2002-2020
Nodes of service gain and loss	Injury: Services at 80% in 2003 and 0% at 2006 (continues in perpetuity). Compensatory action: Services at 10% in 2003 and 100% 15 years later in 2018 (continues in perpetuity).

Table 2. Explanation of HEA parameters and values used in the case study.

The recovery times and service levels for both the injured site and the compensatory action must be specified by placing nodes along the time axis which represent the level of services provided at a given time. This can be done either directly through the graphical interface or manually by inserting the service level and time values into a pop-up dialog box. In its present form, Visual_HEA allows only a linear recovery function between specified nodes. General curvilinear shapes can be specified by multiple closely-spaced nodes. (Later versions of Visual_HEA may incorporate additional recovery functions, e.g. quadratic or exponential). The ease of placing and moving the service level nodes allows different scenarios to be quickly visualized and analyzed. Scenarios can be saved for later analysis by clicking the “Save HEA data” button.

Fig. 1 shows a Visual_HEA panel of data input for the beach renourishment project case study described above:

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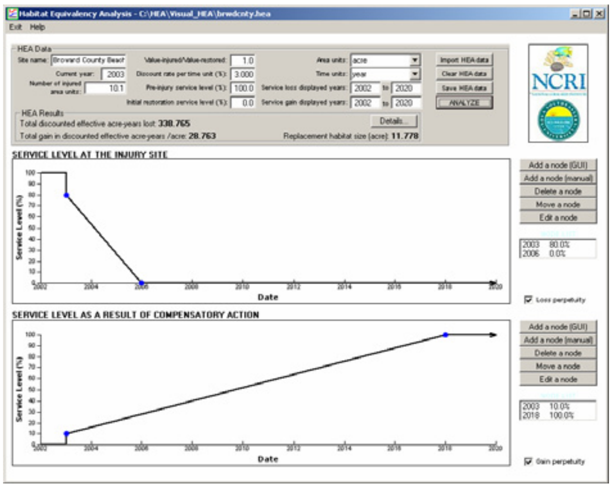

Fig. 1. A screenshot of the main form of Visual_HEA. General program parameters are entered in the top section, and the time history shape functions of lost and gained services are entered on the two graph areas below.

After the initial parameters and the recovery function information have been specified, the analysis can be performed by clicking "Analyze". The results are displayed in an insert labeled "HEA results" placed above the upper panel graph, as shown in Fig. 2.

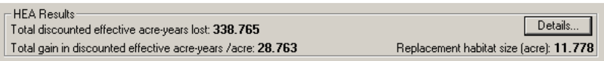

Fig. 2. A screenshot of the results section of Visual_HEA.

The analysis indicates that a compensatory replacement project of 11.8 acres (4.8 ha) will provide service gains equal to the services lost over time in the injured area.

The shaded areas in each panel of Fig. 3 shows the actual amount of services lost and gained over time in a graphical form. The upper plot is a graph of λ_t, while the lower panel is a plot of γ_t. The plots span the period from 2002–2102 in order to show how the effect of discounting provides a closure mechanism for the shaded areas. Actual closure occurs at infinity.

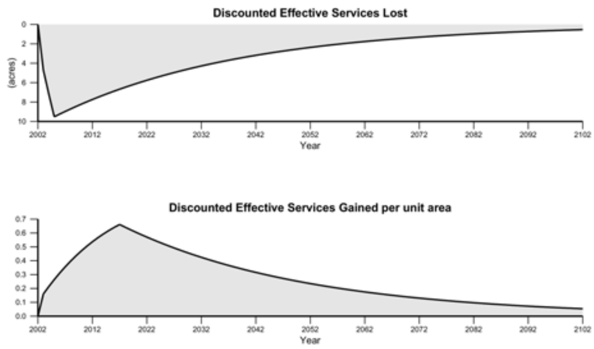

Fig. 3. Graphs of discounted effective services lost (upper panel) and discounted effective services gained per unit area (lower panel).

In order to see the yearly calculation details, the "Details" button is clicked. A new window appears, displaying the values of λ_t and γ_t for each year of analysis. Table 3 shows a summary of these yearly values.

Services lost at the injury site						Services gained at the compensatory site				
Year	**% Service Level (end of year)**	**% Service Loss (end of year)**	**Effective area lost (acre)**	**Discount Factor**	**Discounted effective area lost (acre)**	**Year**	**% Service Level (end of year)**	**% Service Increase (end of year)**	**Discount Factor**	**Discounted effective area lost (acre)**
2002	100.00	0.00	0.000	1.030	0.000	2002	0.00	0.00	1.030	0.000
2003	53.33	46.67	4.713	1.000	4.713	2003	16.00	16.00	1.000	0.160
2004	26.67	73.33	7.407	0.971	7.191	2004	22.00	22.00	0.971	0.214
2005	0.00	100.00	10.100	0.943	9.520	2005	28.00	28.00	0.943	0.264
2006	0.00	100.00	10.100	0.915	9.243	2006	34.00	34.00	0.915	0.311
2007	0.00	100.00	10.100	0.888	8.974	2007	40.00	40.00	0.888	0.355
2008	0.00	100.00	10.100	0.863	8.712	2008	46.00	46.00	0.863	0.397
2009	0.00	100.00	10.100	0.837	8.459	2009	52.00	52.00	0.837	0.435
2010	0.00	100.00	10.100	0.813	8.212	2010	58.00	58.00	0.813	0.472
2011	0.00	100.00	10.100	0.789	7.973	2011	64.00	64.00	0.789	0.505
2012	0.00	100.00	10.100	0.766	7.741	2012	70.00	70.00	0.766	0.536
2013	0.00	100.00	10.100	0.744	7.515	2013	76.00	76.00	0.744	0.566
2014	0.00	100.00	10.100	0.722	7.296	2014	82.00	82.00	0.722	0.592
2015	0.00	100.00	10.100	0.701	7.084	2015	88.00	88.00	0.701	0.617
2016	0.00	100.00	10.100	0.681	6.878	2016	94.00	94.00	0.681	0.640
2017	0.00	100.00	10.100	0.661	6.677	2017	100.00	100.00	0.661	0.661
2018	0.00	100.00	10.100	0.642	6.483	2018	100.00	100.00	0.642	0.642
2019	0.00	100.00	10.100	0.623	6.294	2019	100.00	100.00	0.623	0.623
2020	0.00	100.00	10.100	0.605	6.111	2020	100.00	100.00	0.605	0.605
Beyond					203.689	Beyond				20.167
Total discounted effective acre-years lost:					**338.765**	**Total discounted effective acre-yrs/acre gained:**				**28.763**
						Replacement habitat size (acres):				**11.778**

Table 3. Results from the HEA case study of Beach Renourishment project

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In the summary window, options are provided to save these data in one of two formats. The data can be saved as a text file that can be imported into word processing software. Also, a PostScript file can be created, which can be converted to .pdf format using software such as Abode Distiller©. The PostScript file contains a graph of the time history shape functions of lost and gained services, as well as yearly tabulations of λ_t and γ_t.

Discussion

The assumptions made regarding the time history of lost and gained services form the core of HEA calculations. Visual_HEA allows the user to quickly modify these time histories and analyze various injury and compensatory scenarios. When specifying the time history of the injury and compensatory action, an important assumption in the HEA is whether or not the services lost or gained continue in perpetuity. This assumption can have a significant effect on the calculated size of the replacement site.

For example, in the case study assume all as above, but that the compensatory action begins degrading 10 years after reaching full services (in 2028) and services cease completely 10 years later in 2038. The compensatory action required for this case is 23.6 acres (9.6 ha), versus the 11.8 acres (4.8 ha) required previously. This is because the compensatory action provides gained services which last only a finite amount of time, and hence more compensatory area is required to balance the loss of services. The opposite situation arises when there is recovery at the injury site. In this case, the amount of lost services is less, and hence less compensatory action is required to offset these losses.

When using Visual_HEA, it is important to be aware of the conventions used regarding the placement of nodes. When placing a node at a given time, e.g. year, the tic marks on the time axis indicate the beginning of the corresponding year label. Also to be noted is the fact that the compensatory summary details give the amount of lost and gained services at the end of any given year, as is customary in existing HEA literature.

It is possible to use quarter-years instead of years as the time unit for Visual_HEA. The important item to remember is the user should adjust the discount rate input value per time step so as to maintain the desired annual discount rate.

For the case study, a landscape HEA has been applied to resource injuries. This is useful for relatively uniform landscapes with little difference in biological functions across the injured area. A population HEA approach (Milon and Dodge 2001) could also have been considered where the total injury area would have been allocated into portions based on a percent contribution of organism categories of interest. An individual HEA would then have been performed for each appropriate category using its allocated area.

The current version of Visual_HEA contains limitations which the authors may be able to address in future released versions if there is demand. Among these are time-dependent values for V_j and V_p, non-linear time recovery functions, and monthly or other timesteps.

Summary

Visual_HEA is a computer program that facilitates input of HEA assumptions and parameters and calculates the compensatory action required for a given set of assumptions about injury and compensation. The program allows input of the relevant parameters necessary for analysis, and through the use of an intuitive graphical interface, the input parameters and recovery functions can be quickly changed. The ability to formulate many scenarios using the graphical interface is useful to evaluate alternative compensation strategies.

Future work includes adding more sophisticated capabilities to several aspects of the program , including non-linear time recovery functions and additional timestep options.

Acknowledgements

We would like to thank anonymous reviewers for their helpful comments which improved the manuscript. This work is a result of research funded by the National Oceanic and Atmospheric Administration Coastal Ocean Program under award #NA03NOS4260046 to Nova Southeastern University for the National Coral Reef Institute (NCRI). This is NCRI contribution No. 64.

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