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Research paper

An economic analysis of biochar production using residues from Eucalypt plantations

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ABSTRACT

Producing biochar from organic residues is a potential method to integrate carbon sequestration and residue management costs while enhancing conventional agricultural and forestry production systems. Plantation forestry is an important industry in Tasmania, and is based on large scale plantations of *Pinus radiata* and *Eucalyptus* (*Eucalyptus globulus* and *E. nitens*). The area covered by forestry plantations in Tasmania (on State land) exceeds 100 000 ha, while plantations on private land double this number. Eucalypt plantations are managed primarily for the production of high-value pruned logs for industry; however, unpruned saw logs, peelers, poles, posts and pulp are also produced, and significant quantities of residue are produced as a byproduct. This study was an economic analysis that considered on-site biochar production system using post-harvest forestry residues, with biochar being utilized within the system, or sold as a product. The financial analysis was based on previous experimental outcomes on the use of Macadamia shell biochar in *Eucalyptus nitens* plantations, and the local operating environment in Tasmania; including current forestry procedures used for managing plantations. A number of assumptions were considered concerning a) production costs, b) savings enjoyed by traditional operations, following biochar scenario implementation, and c) biochar sales. The analysis revealed a potential annual income of over 179 k$ (2014 value) and the sensitivity analysis identified the crucial factors responsible for scenario profitability, namely biochar price and final product distribution.

1. Introduction

Forestry is a significant industry in Tasmania, with large scale plantations of radiata pine (*Pinus radiata*, D. Don) and *Eucalyptus* (*Eucalyptus globulus* and *Eucalyptus nitens*, H. Deane & Maiden) which play an increasingly important role in supplying national and international demand for timber. Propagating robust seedlings for planting in the field is an important and expensive part of plantation establishment that influences final yield.

The first Tasmanian hardwood plantations were established in the late 1930's, mainly in the North-West of the State [1]. Most of these were small *Eucalyptus* plantings within patches of native forest. Today, there are approximately 52,000 ha of softwoods and 56,000 ha of hardwoods growing on Tasmanian State forests for the supply of timber to local and interstate industries. Typical procedures to prepare the ground for plantation establishment include harvesting and clearing the slash (harvest residues) from the previous plantation, and soil cultivation and pest control (i.e. herbicides and insecticides). Clearing the harvest residues on a coupe is accomplished through a number of methods; the method chosen depending on the volume and size of residues, the soil type and quality, location of the coupe, and slope. Typically, the residue is windrowed at an inter-row distance of 15–60 m after which it is crushed and burnt [2]. Planting beds are traditionally prepared by a tractor-mounted mound cultivator, creating continuous mounds on top of which the seedlings are planted. Successful establishment during the first two years is crucial for plantation health, and productivity as well as final yield.

Producing biochar from local organic residues may provide greater levels of certainty regarding the stability of recalcitrant soil

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carbon, and increased flexibility when managing residue processing costs in conventional agricultural and forestry production systems. Biochar, however, is not widely used by farmers or foresters in Australia, mainly due to the lack of certainty concerning long-term consequences, yield gains and a lack of ‘know-how’ in quality assurance, transportation, logistics and cost efficiency.

Within agricultural systems, biochar has been added to soils to sequester carbon [3–5] and may maintain or improve soil functions improving desirable levels of porosity, bulk density or water holding capacity [6,7]. It has been reported to bring about positive effects on soil and plant nutrition, but also to have negative repercussions for both soil and plants [8,9]. Despite the emerging use of biochar in agriculture, very few studies have examined its utilization in forestry and other tree-based agro-systems [10]. It has been reported, that charcoal from wildfires mixed with substrates from microhabitats increase shoot-to-root ratio in silver birch (*Betula pendula*) and Scots pine (*Pinus sylvestris*) when studied in a glasshouse in north Sweden [11]. De Luca et al. [12] has also reported increased nitrification rates in the soil after application of wildfire-produced charcoal mixed with ammonium. Therefore it can be speculated that biochar deliberately applied to forestry soils may bring similar effects.

In the current commercial procedures processing of post-harvesting residues is rather connected with costs than benefits incurred by the forestry industry. Producing biochar from post-harvesting residues could serve as an alternative to on-site clearing burns while using the resultant biochar as a soil amendment could provide both agronomic benefits and financial gains. The scenario proposed in this analysis involves the use of post-harvest residues and a mobile pyrolysis unit to produce biochar, a portion of which is subsequently applied to the soil on site. The scenario proposes two other uses of the final product: use within the forestry nurseries and commercial sale into the horticultural market. A financial model was built with Excel (Microsoft®, ver. 2007) to determine if under this commercial scenario, the mobile pyrolysis of forest harvesting residue can be undertaken profitably.

2. Material and methods

2.1. Area and feedstock

It is estimated that an average area of 2000 ha of forestry plantation is harvested and replanted annually in Tasmanian State forests. Annually, the quantity of post-harvest organic residues, specifically slash and litter, vary between 10 and 70 t ha^{-} (Sadanandan Nambiar, Chief Scientist CSIRO, personal communication, project meeting 2011). For modelling purposes an average value of 30 t of woody residues per hectare was assumed. Typically, the water mass fraction of freshly cut wood is approximately 30%, and after being air-dried on site for several months, this is likely to decrease to ca. 12% [13,14]. It is at this approximate water mass fraction (12%) wood residues are considered suitable for either burning on-site or, for conventional kiln combustion to produce energy and other products [15].

2.2. Pyrolyser

There are various mobile pyrolysers available on the market. In this analysis the CharMaker MPP20 mobile pyrolysis plant from the Earth Systems® (VIC, Australia) was considered as the most suitable for the proposed scenario. The unit is designed around a standard 20 foot shipping container and can be easily transported on a truck or trailer. Processing up to 4 tonnes of wood material (moisture content up to 35%) per batch, the unit can produce approximately 1 tonne of biochar after 4 h operation. The unit is intended to operate on large pieces of material (up to 2 m length) in order to by-pass the need for on-site chipping of large volumes of woody matter. The CharMaker MPP20 is equipped with primary heating and emission control (after-burner) systems and supplied by diesel oil during start-up. The unit can operate unattended and has the potential to sequester several kilo-tonnes of carbon dioxide equivalent (CO_2e) per annum through char production [16].

2.3. Agronomic assumptions

A Field trial was established on the 18th Oct 2011 in Florentine valley, South-West Tasmania (42°38′S, 146°27′E; Forestry Tasmania coupe FO031Z). Six rates of biochar (0–20 t ha^{-1}) were combined with 3 rates of fertiliser (0, 50 and 100% of the full commercial fertiliser dose) to produce a factorial combination of 18 different treatments. The agronomic assumptions used within the model were based on the results of plant growth and chemical changes in the soil and leaf material in response to fertiliser and biochar application rates. The assumptions were also based on results of a pot trial with *E. nitens* seedlings performed within a wider biochar project [17]. Plantation soil type, location and size were also used to emulate the parameters associated with a typical plantation site in Tasmania and these were included in the set of model specifications. The influence of biochar on chemical fertility in-field was compared to di-ammonium phosphate (Impact Fertiliser®) applied at a rate of 200 g per seedling. Soil in the field experiment was classed as a brown dermosol (Australian Soil Classification System). The nutritional analysis of soil and leaf tissue of growing trees was performed on 4 occasions during the first 14 months following planting.

2.4. Biochar

The model scenario presumed the use of biochar produced from an *E. nitens* residue feedstock, however due to availability, the agronomic assumptions were based on data using macadamia shell biochar and its effect on eucalypt productivity. While macadamia and *E. nitens* biochars are both wood-based products it is important to emphasize that the effects of their application to soil will most likely vary.

The macadamia shell char was made in South Africa in the Mpumalanga province, Alkmaar. The feedstock was provided by Golden Macadamias Pty Ltd. and collected from 3 to 30 years old orchards of *Macadamia integrifolia* (Maiden & Betche) in 2008. The char was made at the HTT (highest temperature treatment) of 480 °C and residence time was 180 min. The char was stored and then shipped to Australia in 1.2 m^2 bags made of polypropylene fabric. After arrival in Freemantle WA, it was stored in the same bags until April 2011, when it was shipped to Tasmania in plastic bins and stored before application in eucalypt plantation trial in September 2011. Relative to other biochars described in the literature, analyses have characterized the macadamia shell biochar used in this study as high in potassium and sodium, moderately high in carbon content and low in nitrogen (N) and phosphorus (P) [18–21]. Further characteristics of the applied biochar are presented in Table 1.

2.5. Model building

The model consisted of several formulae (Table 2) and used projected values to calculate total annual benefit. The total benefit calculated by the model was based on three main components: 1) a cost/benefit analysis of production that included standard operating costs and savings that accounted for fertilisation, site cleaning/preparation after plantation harvesting, and weed control during plant establishment; 2) cost/benefits arising directly from biochar production and application, this calculated with respect to

Table 1
Macadamia biochar chemical and physical characteristics (pyrolysis production conditions, element composition and polycyclic aromatic hydrocarbon content (Acenaphthylene, Acenapthene, Anthracene, Benzo-a-anthracene, Benzo-a-pyrene, Benzo-b&k-fluoranthene, Benzo-ghi-perylene, chrysene, dibenzo-a,h-anthracene, Fluoranthene, Fluorene, Indeno- 1,2,3,cd-pyrene, Naphtalene, Phenanthrene, Pyrene).

Test	Temp made	pH(H_2O)	Nitrogen	Carbon	NH4-N	NOx-N	Ca	Fe	K	Mg	Na	P	PAHs
Unit	C degrees		%		Mg per L		Mg per kg						Mg per kg DMB
Value	450–480	8.76	0.43	78.03	3.5	0.1	3700	1211	21,900	1700	3200	2400	<0.10

Table 2
Explanation of some formulae used in the Excel model to calculate the total income resulting from the implementation of Biochar Scenario in Tasmania.

Item/operation	Calculations
Number of coupes per annum	= number of operating days per year × number of tonnes processed per year ÷ total tonnes processed in an example coupe
Pyrolyzer maintenance cost per annum	= unit capital cost × maintenance cost per annum as % of capex
Seedling raising saving per hectare	20$ at biochar application rate $\geq$10 t ha^{-1} 15$ at biochar application rate 5–10 t ha^{-1} 10$ at biochar application rate 1–4 t ha^{-1} 0$ at lower rates
Site preparation savings per ha	400$ when processed wood per hectare $\geq$30 t 300$ when processed wood range from 29 to 20 t ha^{-1} 200$ when processed wood range from 19 to 15 t ha^{-1} 100$ when processed wood range from 14 to 10 t ha^{-1} 0$ when less wood is processed
Fertilization savings per hectare	90$ at biochar application rate $\geq$3 t ha^{-1} 45$ at biochar application rate 1.5–2.9 t ha^{-1} 0$ at lower rates

carbon prices, current market prices for biochar and financial gains associated with using biochar in forestry nurseries and; 3) cost/benefit of facility and process costs associated with incorporation; namely pyrolyser capital cost, operating costs and expenses involved in handling feedstock and biochar. As the model was based on sharp financial assumptions, it returns exact income values rather than a range of potential financial benefits. Selected formulae are further described in Table 2 and some of the values included when building the model are presented in Table 3.

2.6. *Sensitivity analysis*

Using a number of different scenarios, sensitivity analyses were performed to determine which parameters the model was most sensitive to. The factors changed in each scenario included pyrolyser capacity, number of pyrolysis units, market fluctuations in the price of carbon and biochar, changes to the distribution channel shares, and an increased utilization of harvest residue (Table 4). Only one factor was changed at a time.

Table 3
Agronomic, capital and operating costs, and product assumptions used for building the cost-benefit model for Biochar Scenario case study in Tasmania.

Pyrolyser	Assumption	Justification
Mobile pyrolyser capital cost	250,000$	Including the delivery
Mobile pyrolyser useful life	10 years	Advised by manufacturer
Labour cost per batch	30$ per hour	The costs of a tractor operator
Cost of moving pyrolyser between example -coupes	300$	Loading and transport of the pyrolyser by truck over 20 km (average distance in between example coupes)
Average number of batches a day	3	As advised by manufacturer
Model coupe size	30 ha	Estimated in co-operation with Forestry Tasmania
Waste wood pyrolysed per hectare	15 t	Based on wood moisture and waste wood required to be left for soil nutrition
Average batch size	4 t	Pyrolyser capacity
Cost of delivering waste to the edge of coupe	10$ per tonne	Calculated for x type machinery operation and time
Feedstock to produced biochar ratio	4:1	As advised by manufacturer and amended using information available for other similar systems
Tonnes of CO_2 stored in one tonne of biochar applied in the soil	3	Based on the literature [15]
Reduced costs of seedling establishment associated with biochar application	10$ per ha	Biochar application rate of 1–5 t per ha, supporting the early growth of seedlings and increased drought resistance resulting in lower seedlings mortality (based on field and pot experiments)
Site preparation savings	200$ per ha	$\geq$15 t wood processed per hectare
Fertilisation savings	10–90$ per ha	Application rate of 1.5–3 t per ha
Final product distribution (onsite: nurseries: sale)	60%:10%:30%	Based on the forestry needs and market demand
Biochar: CO_2	1:3	Estimated on the basis of available literature of CO_2 equivalents
Price for CO_2	10$ per tonne	Estimated market price
Biochar price	1000$ per t	Current average biochar price in Australia
Distance from the coupe to collection site	100 km	Plantation distribution in Tasmania (average)

Table 4
The list of scenarios used to determine the crucial factors in the sensitivity analysis.

No	Scenario
0	Base scenario
1	Bigger pyrolyser (MPP40, capacity of up to 10 t/batch)
2	Final product distribution 70 (field application):10 (nursery use):20 (sale)
3	Increasing amount of processed wood/ha to 30 t
4	Increasing carbon price to $20
5	Biochar price 2000$
6	3*MPP40

3. Results

Using the base parameters, the model indicated a net annual return of just over 179 k$ (Table 5). The greatest contribution to annual revenue was derived from biochar sales while the greatest cost was connected to pyrolyser operations. Scenario 1 presumed the use of a larger pyrolyser (10 tonne batch). Under these conditions, capital and operating costs increased with volume, but were offset by economy of scale that led to a lower unit cost per tonne of wood processed. Changing the distribution channels by increasing field application by 10% (Scenario 2), and the commensurate decrease in sales reduced net profits by 54% on the base scenario (Table 5). Increasing the quantity of processed wood residue by 100% (Scenario 3) did not produce any gains, as this also created an equivalent increase in feedstock processing costs (Table 5, Fig. 1). Increases in the carbon price by 100% (Scenario 4) increased profit by 10% while a doubling in the price per tonne of biochar (Scenario 6) would lead to a 166% increase in net profit. The last scenario examined the benefits associated with the use of three pyrolysers of a larger size (MPP40) to process biomass, and is here the model predicted an increase in total return more than 5 times higher than the base scenario (Table 5).

The optimum amount of timber residue processed per hectare under the base scenario equated to 20 tonnes, and lower or higher quantities decreased the total benefit. Above 20 tonnes, profit decreased, particularly at a processed wood volume of 25 t per hectare, where costs associated with site clearing and a second insecticide application proportionally increased costs per tonne biochar per hectare. Fig. 1B and C shows a strong linear dependence of total project benefit on the price of carbon and biochar. The intercept in Fig. 1B indicates that if the carbon benefit was removed from calculations, the project remains profitable (at 86% of the base scenario). This suggests that a carbon price was not a crucial factor for financial feasibility in this model. In contrast to this, there was a steep linear dependence of profitability on the market price of biochar (Fig. 1C). The slope of this regression indicated that for each 1 $ increase in the price of biochar, a net benefit of 288 $ was derived (Fig. 1C). Thus a biochar price of 600 $ per tonne above the base scenario doubled the return, while a price fall to less than 400 $ per tonne resulted in an equally strong negative return. When the final product distribution was altered (Fig. 1D) by increasing sales volume into the horticultural market at the minimum cost of 400 $ per tonne, the profitability of the project model also increased rapidly. Depending on the quantity of biochar diverted from field application, the amount available to the market varied between 288 and 966 tonnes per annum.

4. Discussion

The evaluation of this model has shown that onsite biochar production from forest residues may be feasible, but is dependent on receiving a minimum of 400 $ per tonne ($10 per 25 kg) in the amenity horticulture or agricultural market for 30% of the biochar produced. The model also demonstrated a marked sensitivity to biochar sales volume and market price, indicating high profit or losses might occur in an unstable market.

Tasmania's capacity to produce large volumes of biochar is significant, the State having a sustainable supply of forest biomass of at least 3 green Mt y^{-1}, this arising predominantly from plantations, with a smaller fraction coming from harvesting native forest regrowth [15]. As logic would dictate, the sensitivity analysis confirmed that using a larger capacity pyrolyser (10 t per batch) increased biochar production, and taking advantage of this would necessitate a market willing to consume an increased product volume. Using a single smaller pyrolyser (base scenario), the model predicted that sales of biochar through horticultural channels could exceed 1000 t per year. The increased capacity pyrolyser scenario doubled the predicted product volume, while increased feedstock volumes (scenario 5) may produce six times more biochar than the base scenario. Thus although there is a significant quantity of forest residue available in Tasmania, the biochar market in Australia is currently small, and selling large quantities of biochar would be contingent on creating greater demand in the horticultural and agricultural sectors [22–24].

Modelling a higher price per tonne paid by government for CO$_2$ sequestration (scenario 3) did not have great sway on the total project benefit (+/− 15% of the base scenario benefits) and thus carbon price was concluded to be much less important in this simulation when compared to biochar price or pyrolyser capacity. Profitability of the model was highly sensitive to biochar market price and thus appeared critical to project feasibility. The model was also sensitive to moving allocation away from the horticultural distribution channel (scenario 2), and decreased net income by −52%, this reflecting that per unit gain in revenue from field application was not commensurable with that arising from biochar sales. Thus while application within an operational context appeared economically robust, stability of the models profitability was heavily dependent on market forces outside of this arena. Overall, the model predicted that ‘real world’ implementation would be heavily dependent on the horticultural markets ability to absorb a minimum volume of 30% of the residue pyrolysed at a minimum price of 400 $ per tonne [24].

Model evaluation: The model's sensitivity analysis was based on only changing one factor at a time. To fully understand the effect of

Table 5
Results of model run based on basic assumptions and results of sensitivity analysis.

No	Scenario	Total benefit ($)	Change to base
0	Base assumptions	179,514	–
1	Bigger pyrolyser (MPP40, capacity of up to 10 t/batch)	375,029	$195,515 (117%)
2	Final product distribution 70:10:20	83,284	−$96,230 (−52%)
3	Increasing amount of processed wood/ha to 30 t	179,564	–
4	Increasing carbon price to $20	189,844	$10,330 (10%)
5	Biochar price $2000	460,546	$281,032 (167%)
6	3*MPP40	1,124,270	$944,756 (552%)

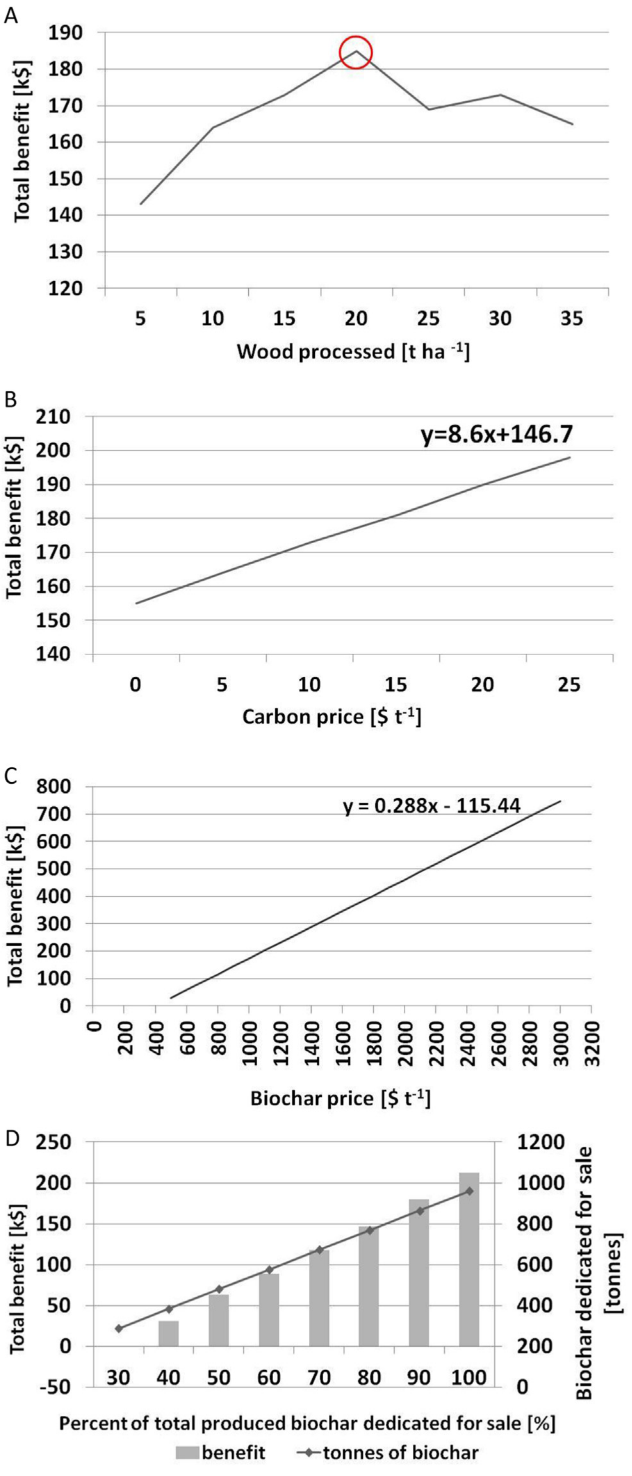

Fig. 1. Sensitivity analysis of biochar scenario model($) in relation to (A) amount of residue wood processed per ha of plantation, (B) carbon price per tonne of CO_2 stored, (C) price per tonne of biochar, (D) total benefit of the proposed scenario and biochar amount dedicated for sale in relation to percent of total biochar produced, dedicated for sale. The biochar market price was estimated at 400 $ per tonne.

each factor and find the nexus at which all parameter levels converge to derive maximum advantage, a more complex sensitivity analysis including simultaneous changes in parameterisation was needed, but was beyond the scope of this study [25]. There are also financial benefits indirectly derived from pyrolysing forest residues not considered in the analysis, with community approval to limited on-site burns, decreased fire risk and reduced smoke disruption to local communities [14,15] likely to derive some pecuniary as well as non-pecuniary remuneration. The model strengths lay in the assumptions based on real commercial plantation management parameters, and known plantation growth rates under local conditions in the Florentine Valley, Tasmania. If the model was used in a different context the assumptions related to the benefits of biochar application would require modification according to local environmental conditions [23]. The main simplification used in the model was the supposition that only post-harvest residue wood is used for biochar production. Other available residues include: a) plantations that do not grow as expected during the first years and terminated; b) thinning residues, a common residue in plantation management and currently used for pulpwood production; c) private forestry plantations; d) wood processing industry (i.e. Sawmill waste); e) and residues from native forests management practices [14,15].

The model allowed for a reduction in fertiliser application when using di-ammonium phosphate with macadamia shell biochar, and this assumption may change if different fertiliser formulations or biochars are used. Even though eucalypt and macadamia feedstocks are both lignified cellular solids with relatively low density and high strength, the eucalypt, an anisotropic material, would produce a char with different characteristics to that made from macadamia [26]. The macadamia testa is comprised of isotropic material of small stone cells and likely to have greater porosity and surface area associated with its finer structure when compared to the larger vessels of vascular tissue found in timber residues. While the properties of the two materials are somewhat divergent and the simulation may be marginally improved through the inclusion of parameters based on eucalypt char, it is unlikely to have a significant impact on the model outcomes.

5. Conclusions

The results presented here indicate that biochar production from eucalypt plantations residue wood under Tasmanian conditions has a potential to bring financial benefits to the forestry industry. The Excel model based on production costs and financial gains resulting from savings in standard forestry procedures and biochar sale can be adjusted to fit local conditions. The sensitivity analysis revealed that the total benefit of the project is greatly dependant on the final product distribution and biochar price. Therefore detailed local market studies would be required to ensure the scenario financial feasibility.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2015.06.015.

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