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The influence of organic litter on the erosive effects of raindrops and of gravity drops released from desert shrubs

Nicole Geddes, David Dunkerley *

Department of Geography and Environmental Science, Monash University, Clayton, Victoria 3168, Australia

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Abstract

This paper reports on a laboratory study of the effects of water drop impacts on litter and sand splash beneath desert shrubs. Individual drops of 5.7 mm diameter were released from heights of 0.5, 1.0, and 1.5 m (selected to encompass the height range of typical desert shrubs) onto targets of bare or partially litter-covered, saturated fine sand. The natural litter, largely derived from the saltbush *Atriplex vesicaria*, was collected from desert shrubland sites in western New South Wales (NSW). The drop impacts caused both sand and litter particles to undergo splash displacement. The mass of sand splashed was found to increase with drop fall height, while mass of litter particles splashed did not vary significantly with fall height. Weights of sand moved by airsplash were significantly diminished by surface litter applied at the rate of 200 g/m^2. These findings indicate that gravity drops released from desert shrubs may provide both an erosive force beneath these plants, and a means for dispersing litter from the plant base into the surrounding landscape, where litter may continue to affect hydrologic and erosional processes. By restricting splash of mineral particles, litter acts to limit soil splash from beneath shrubs, and in this way may contribute to the persistence of plant mound microtopography that is common in desert shrublands. Under open-field conditions, large raindrops delivered in convective showers must cause similar airsplash transport of litter particles, thus playing a role in the distribution of litter within the landscape. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Water erosion; Soil erosion; Broken Hill Australia

* Corresponding author. Tel.: +61-3-9905-2914; Fax: +61-3-9905-2948; E-mail: david.dunkerley@arts.monash.edu.au

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1. Introduction

Litter may cover 5%–50% of dryland soil surfaces. For example, a range of 22.0%–71.6% litter cover was documented on study plots within a semi-arid sagebrush (*Artemisia tridentata*) rangeland in Idaho, USA (Johnson and Gordon, 1988). Thus, while it has often been argued that desert soils are bare and exposed to direct raindrop impact (e.g., Mabbutt, 1977), a widespread organic litter layer may intervene. This is especially so in the vicinity of dryland shrubs, whose leaf and flower parts often thickly mantle the underlying and nearby soil surface. Dryland shrubs may thus be thought of as significant 'point-sources' for organic litter. There are also 'diffuse' sources in the forbs and ephemerals that appear in the interspace following rain. In more humid areas, the effects of crop mulch on soil splash from tilled agricultural soils have been studied experimentally (e.g., Kramer and Meyer, 1969; McGregor et al., 1988), and splash detachment has been shown to decline steadily with mulch cover fraction. Singer et al. (1981) showed linear decline with cover fractions spanning the range of 22%–96%. But these findings are based principally on immobile litter, either natural straw mulch or artificial mulch (e.g., Singer and Blackard, 1978; Kramer and Meyer, 1969). Further, there is much less evidence from drylands, especially relating to the role of litter in altering the nature of particle detachment by splash. Many crop mulch particles are too large to be readily transported by splash or shallow flow, and hence act to protect the soil surface by absorbing raindrop impact energy and limiting flow velocities. Smaller particles, on the other hand, may themselves undergo splash transport, and may float in water. They may therefore modify splash mechanisms differently from large litter particles, and become more mobile in surface runoff. In the context of drylands, especially, these topics remain almost unexplored.

The experimental work reported here thus had two goals.

(1) To investigate whether organic litter particles could be entrained and transported by airsplash as might arise from gravity drops falling from a shrub canopy. If so, such splash would provide one mechanism for the initial dispersal of plant litter away from the point-sources of abundant litter located beneath shrubs. We know of no prior data on the splash transport of dryland litter particles.

(2) To investigate how the presence of small amounts of surface litter modifies the intensity of any associated airsplash of mineral particles. The formation of shrub mounds by the net inward splash of mineral particles would clearly be aided if, at the same time, shrub litter restricted the outward splash of these same particles by gravity drops striking the surface beneath the plant. Additionally, we were interested to know how litter dispersed across the landscape might influence splash detachment of mineral particles under open-field conditions, where similarly large water drops can be delivered from intense convective showers (Mason, 1971).

2. Research context—the role of litter in drylands

Organic litter materials exert a range of incompletely-known influences on hydrologic and erosional processes in arid and semi-arid (dryland) landscapes. Relatively smooth, low-gradient surfaces are common in the Australian drylands and elsewhere, and sheetwash is commonly perceived to be a widespread form of surface runoff across these landscapes (Mabbutt and Fanning, 1987). Because of the lack of significant surface microtopography, the behaviour of these flows may be influenced by organic litter on the surface. Logs and other large pieces of litter may constitute 'islands' of fertility where sediments and nutrients are trapped (e.g., Tongway et al., 1989). But litter particles of many sizes exist, and it seems likely that there is a hierarchy of hydrological and erosional effects spanning this range. The accumulation of many small litter particles to form composite litter dams or barriers (Fig. 1) may permit even quite small particles to modify sheetflow movement. When lodged against and among obstacles such as plant stems, masses of litter particles may form sinuous barriers of up to 5 cm height and tens of centimeters in width, oriented normal to the contour. These lead to the trapping of sediment, and clearly modify the patterns of flow depth and speed across the slope. It seems likely that localised ponding behind these barriers would delay the onset of integrated runoff (i.e., spatially continuous flow) across the surface, and also lower mean flow velocities. In small storms, sufficient capacity might exist in pre-existing litter barriers to prohibit totally the development of such continuous runoff across the landscape so that a sloping surface might remain partially or wholly compartmentalised by litter dams. In turn, we have observed that the impoundments of sediment may become sites where plant germination takes place. The composition of the organic litter

Fig. 1. A typical litter-bearing surface in the Fowlers Gap area, western NSW, Australia. Litter barriers, with associated trapped detritus and fine sediment, can be seen lodged among small plants. The bare surface, which carries a few quartz stones, is extensively colonised by cyanobacteria. Slope and water flow direction is from top to bottom; scale bar marked in cm divisions (photo by D.L. Dunkerley).

that is involved in processes such as the formation of litter dams is quite variable, but commonly includes leaves and leaf fragments, flowers, fruiting bodies, bark, small twigs and branch fragments, together with a component of animal dung and seeds. Litter dams reflect active downslope transport and subsequent accumulation of the organic litter of which they are built, but we are aware of no literature on the conditions required for the entrainment and transport of such materials in desert landscapes, nor any dealing with related effects on flow depths or velocities.

Desert shrubs constitute point-sources of organic litter, and after appropriate seasonal weather conditions, large accumulations of leaf and other plant parts may build up beneath them. Commonly, the shrubs themselves grow on small prominences or mounds that may be the result of a net inward splash transport of mineral particles from the surrounding surfaces that are exposed to intense raindrop impact (Johnson and Gordon, 1988; Parsons et al., 1992). The growth of shrubs on local high points suggests that, since these stand above levels normally inundated, litter is unlikely to be dispersed across the landscape from the point-sources beneath shrubs by entrainment into surface runoff. Instead, runoff follows the lower-lying areas in the intershrub space (Abrahams et al., 1995). Wind provides one means of immediate dispersal across the landscape, but the seasonal accumulations of plant detritus observed beneath shrubs in western New South Wales (NSW) indicates that considerable quantities fall directly to the soil surface.

In the present work we focus on one possible means of litter dispersal: the dislodgment of litter particles by water splash at the soil surface beneath shrub canopies. Desert shrubs release gravity drops from the undersides of branches, as well as from the leaf canopy. Gravity drops are defined as those large drops which are released from plants when the raindrops intercepted by the plant (incident drops) merge and become too heavy to remain on the plant foliage (Moss and Green, 1987). These can form even in rain of low-intensity as smaller drops merge on the plant surfaces, eventually falling when their weight overcomes the surface tension forces retaining them. Gravity drops may fall from outer branches directly to the soil surface, or fall through gaps within the plant canopy. Fall heights may be significant, as shrubs such as the black bluebush, *Maireana pyramidata* may exceed 1.5 m in height (Cunningham et al., 1981). Large individuals of the bladder saltbush may reach 1 m. It is unlikely that many drops falling from the uppermost parts of shrubs would reach the ground without being intercepted by lower parts of the canopy; nonetheless, some shrubs display quite open structures and offer relatively little obstruction to the path of falling drops.

The dimensions of gravity drops released from plants has been studied using specimens of many plant species. For example, Brandt (1989) found a mean gravity drop size of 4.95 mm, with drop sizes being normally distributed around the mean size and reaching a maximum diameter of about 7 mm. Moss and Green (1987), who tested leaves from 28 plant species, found an overall mean gravity drop diameter of 5.3 mm. Such drops are known to be capable of significant soil splash on agricultural soils. Indeed, Noble and Morgan (1983) found that gravity drops released from Brussels sprouts plants caused splash under the canopy that was of the same intensity as that caused in the open by raindrop impact. We are aware of no corresponding data for dryland shrubs and soils.

The erosivity of gravity drops is strongly dependent upon their height of fall. Moss and Green (1987) classified the potential erosivity of gravity drops falling from different heights within a plant canopy, showing that as fall height increases there is a trend of increasing erosivity that approaches a limit when terminal fall velocities are achieved. Their classification was as follows:

$<$ 30 cm: insignificant soil disturbance;
30 cm–1.0 m: significant gravity drop erosivity;
1.0–2.5 m: high and increasing gravity drop erosivity;
2.5–6.0 m: high and more slowly increasing gravity drop erosivity;
$>$ 6.0 m: gravity drops approach terminal velocity when released from this height, so that little increase in erosivity occurs.

These suggestions were derived from unprotected sand surfaces, and may not be directly applicable to dryland surfaces carrying organic litter covers. Water drop impact on surfaces carrying organic litter appears to be in need of investigation for other reasons. We have observed that clumping of floating fragments may then occur, effectively reducing the fraction of the soil surface actually covered by litter. Small litter particles may also be prone to splash displacement, so that a lesser degree of protection might be afforded to the regolith surface beneath them than beneath straw mulch or other crop residues that are too massive to undergo airsplash. It is, therefore, not clear that the same kinds of splash inhibition effects would arise from small fragments of dryland litter as have been found for extensive covers of immobile straw or leaf mulch on tilled soils.

3. Materials and methods

We examined the sand mass splashed from a target container struck by a series of individual water drops released from three different heights above it. During some runs, litter particles were distributed over the sand surface, while in others, bare sand was tested.

3.1. Size of gravity drops

The experiments were carried out using simulated gravity drops of 5.7 mm diameter. One hundred drops were collected and the mean diameter calculated from their aggregate weight. The drops were created using a 35-cm^3 disposable syringe with the outlet fitted with a short length of plastic tubing of 5 mm inside diameter and 8 mm outside diameter. This provided a sufficiently large surface on which drops of the desired size could gather. The syringe was filled with distilled water and slight pressure was exerted on the plunger to induce the drops to fall.

3.2. Experimental arrangement

Three fall heights of 0.5, 1.0 and 1.5 m were used during the experiments to span the heights of shrub canopies observed in the arid shrublands of western NSW (Dunkerley and Booth, 1999). The syringe was clamped tip down on a retort stand. At each of the three heights, 30 gravity drops were released into a 100-mm diameter glass Petri dish target. This contained 60 g dry weight (approximately 6 mm depth) of medium, acid washed sand (80% grains by weight lying between 0.2 and 0.35 mm diameter). The targets were rotated at intervals to avoid cratering of the target sand by repeated impacts. The sand filled Petri dishes were saturated with distilled water and carried a 3-mm film of surface water. This simulated a ponding depth often observed in the field under the outer parts of shrub canopies. Very close to shrub stems, on the porous central parts of shrub mounds, only localised and thinner ponding depths are reached, while greater depths occur in shrub interspace. A 200-mm high, cylindrical paper tube was then placed to surround the Petri dish to collect any material splashed outward. For each fall height, the set of 30 drop impacts was replicated five times under identical conditions. This was done because the litter treatments (e.g., the precise surface density or total number, weight and size of litter particles) could not be replicated exactly with the natural litter used, and to increase the reliability of averages determined from the experiments in light of possible variation in sand packing density, drop trajectory, etc.

Once the 30 gravity drops had been released into the Petri dishes, the paper tube was removed and allowed to air-dry while standing upright on a clean sheet of paper. The Petri dish containing the remaining sand was dried at 105°C overnight and re-weighed. Once dry, the material collected on the paper tubes, and any which had fallen onto the paper sheet, was brushed off and weighed on a laboratory balance to 0.1 mg.

3.3. Litter trials

The same experimental procedure using three fall heights, 30 water drops, and five replicates was carried out for sand which had been partially litter-covered by adding 1.3 g of dried litter collected from Fowlers Gap Arid Zone Research Station in arid western NSW. This amounts to approximately 200 g/m^2 litter, a loading that we have observed commonly in shrublands in this field area (for comparison, Blackburn et al. (1992) reported litter loadings of 168 g/m^2 in a Texas bunchgrass site). The majority of the litter was made up of flower and leaf parts from the bladder saltbush (*Atriplex vesicaria*), along with bark and twig fragments, various spiny or hairy fruiting bodies (largely from *Bassia* spp.) and some animal dung. Typical dimensions for litter fragments are given in Table 1, from which it can be seen that individual fragments weighed from a few milligrams to perhaps 45 mg. Photographs of the litter-bearing targets were overlayed with grids having 360 nodes and the proportions of litter and bare

Table 1
Typical mass and size for the three principal components of the organic litter used in the sand splash experiments

Litter component	Typical masses (mg)	Typical dimensions (mm)
Saltbush leaf or leaf parts	7.0–15.6	up to 17 mm long and 6 mm at widest point
Fruiting body (largely from *Bassia* spp.)	up to 38.3	up to 6 mm diameter
Twig fragments	4.6–45.2	length of up to 35 mm

Table 2
Results summary for sand splashed from bare sand targets

Fall height (m)	Mean mass of sand splashed (g)	Standard deviation (g)
0.5	0.0018[a]	0.0013
1.0	0.0300[a]	0.0255
1.5	0.0997[a]	0.0683

Means bearing the same superscript (a) are statistically different ($p = 0.05$) (small-sample t-test).

sand found by tallying point-counts. Results showed that the litter typically provided approximately 50% cover on the splash targets. This accords well with data collected from many 1 m^2 plots in the Fowlers Gap shrublands (Dunkerley, 1998) that revealed a mean of 45% litter cover. Similar litter cover fractions have been reported from drylands elsewhere (e.g., from Nevada, USA by Blackburn (1975) and from Idaho, USA by Johnson and Gordon (1988)). The dry material (sand and litter) splashed onto the paper tubes was collected as before and weighed; the litter from the splashed material was then separated manually using jewellers forceps. The remaining sand, without the litter, was then re-weighed, so providing a measure of the mass of litter particles airsplashed from the target dish.

4. Results

Table 2 (above) and Table 3 (below) summarise the results found for the bare and litter-bearing splash targets.

4.1. Sand splash in the presence of litter

Small sample t-tests (Freund, 1974; p. 281) were used to determine whether the mass of sand splashed was significantly different between the bare sand and the litter-bearing treatments. Differences having a probability of chance occurrence of less than 0.05 were taken as significant. The gravity drops were found to splash significantly more sand from the bare sand targets than from the litter-bearing targets when falling from 1.0 to 1.5 m (Fig. 2). For the lowest height tested, 0.5 m, the masses of sand splashed were not significantly different between the treatments.

Table 3
Results summary for sand and litter splashed from litter-bearing targets

Fall height (m)	Mass of sand splashed (g)		Mass of litter splashed (g)	
	Mean	Standard deviation	Mean	Standard deviation
0.5	0.0022[a]	0.0014	0.0016[a,b]	0.0013
1.0	0.0046	0.0060	0.0059[a]	0.0046
1.5	0.0205[a]	0.0183	0.0205[b]	0.0192

Means in the same column bearing the same superscript symbol are significantly different ($p = 0.05$) (small-sample t-test).

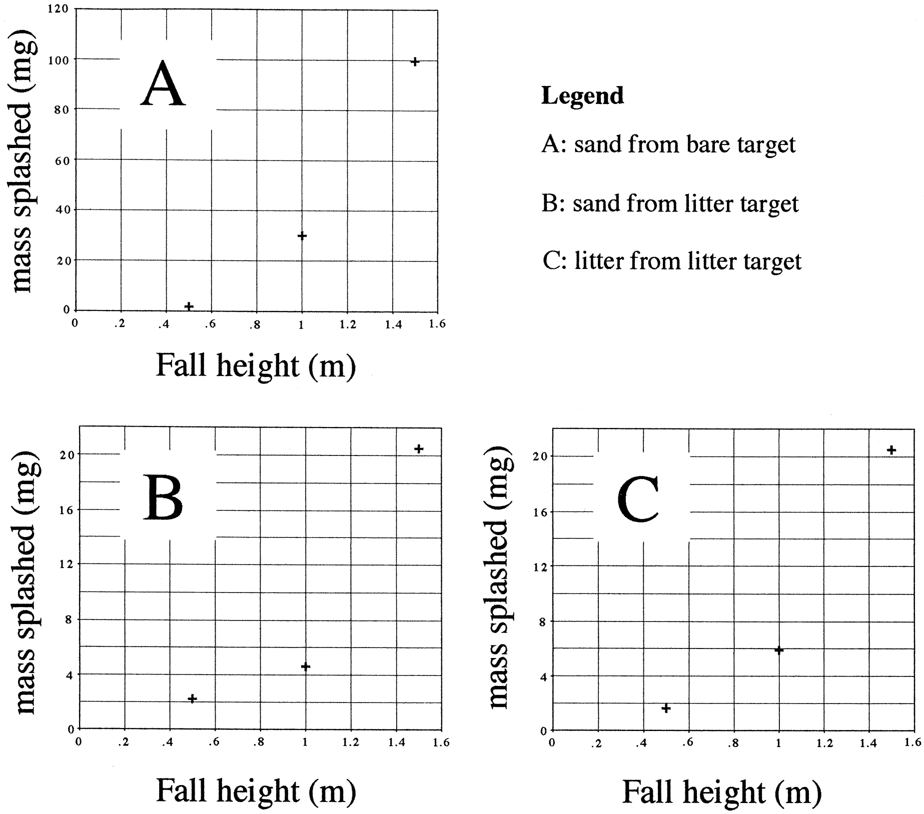

Fig. 2. The relationships between mass of splashed sand and litter for bare sand targets (A) and for litter-bearing targets ((B) sand splash mass; (C) litter splash mass) for all fall heights.

4.2. Variation of sand splash mass with droplet fall height

An examination of the relation of sand splash mass from the bare sand targets with drop fall height showed a significant difference to exist between 0.5 and 1.0 m, 1.0 and 1.5 m, and 0.5 and 1.5 m. Similar comparisons for the litter-bearing targets and the mass of sand splashed showed significant differences between 1.0 and 1.5 m, and 0.5 and 1.5 m. No significant difference was found between 0.5 and 1.0 m.

The trend of the data indicates that as the fall height of the gravity drop increases, so too does the mass of sand splashed. The relationship between mean splashed sand mass and drop fall height was best described by a logarithmic model, as follows:

$$\log(\text{splashed sand weight, g}) = -3.19 + 0.97\ (\text{fall height, m})$$

for which $r^2 = 0.96$ (standard error: 0.13).

This is in accord with generalised non-linear models of the splash process (e.g., Park et al., 1982).

The small mass of sand lost at 0.5 m is a major factor influencing the non-significant statistical results obtained. Drops falling from this height may be close to a threshold below which too little energy is delivered to the surface to cause grain dislodgment (Sharma et al., 1991). However, we recorded displacement at all fall heights and the results cannot confirm the existence of such a threshold.

4.3. Variation of litter splash mass with droplet fall height

Comparisons between the mass of litter lost from the litter-bearing targets showed non-significant differences between 0.5 and 1.0 m, 1.0 and 1.5 m, and 0.5 and 1.5 m. This indicates that there was little change in the mass of litter lost, even when the fall height was increased. This may indicate that the low-mass litter particles were displaced easily even by drops released from the 0.5-m fall height, and that litter abundance was limiting at greater fall heights. In this way, all litter within the zone of influence of a drop impact may have been splashed at all heights tested.

5. Discussion

Our experimental results indicate that litter particles can be entrained and transported by airsplash. Indeed, for drops falling 1.0 m onto litter-bearing targets, a greater mass of litter than of sand was splashed. We conclude that airsplash does provide a means by which litter particles can be dispersed into the landscape from point-sources located beneath shrubs, and by which litter may be redistributed under the open-field conditions of the wider landscape. Intense convective storms can deliver drops of the size used in our experiments, and these arrive at the surface at considerably greater speed than was the case in our experiments.

Our results also show that a significant reduction in sand splash occurred in the presence of relatively small amounts of light-weight litter. Statistically significant effects were shown for the 1.0- and 1.5-m fall heights. Our interpretation of this finding is that the fluid displacements associated with drop impact are modified by the presence of litter particles. Drop splash onto a water-covered surface involves cratering of the water, rapid outward jetting, and subsequent inward flow as the crater collapses and is refilled. Soil dislodgment by splash is thought to involve the tensile failure of small prominences when these are struck by high velocity outwardly-directed lateral water jets thrown out from the point of impact (Huang et al., 1982) or shearing of particles by the outward flow (Ferreira and Singer, 1985). The lateral jets achieve speeds of more than twice the impact speed of the striking drop (Harlow and Shannon, 1967). Soil particles are also thought to be lifted away from the surface by inward return flow as impact craters within ponded water collapse and are refilled (Ferreira and Singer, 1985). Both outward jetting and inward return flow could be affected by litter particles contained within the surface water film or floating within and upon it. Drag created when litter particles were pushed or pulled across the surface of the mineral soil would consume, by viscous dissipation, some of the available drop impact energy that would not be dissipated in the absence of litter. Spiny fruiting bodies could be especially effective in creating drag. Viscous dissipation by litter would result in less energy being available for soil dislodgment. This effect would arise even when the drop impact point was on bare soil (i.e., at a point between litter particles, rather than striking a particle directly), were there nearby litter particles that would have to undergo lateral displacement because of the oscillatory fluid flows associated with drop impact. A piece of litter dragging on the mineral surface would extract energy from the droplet impact on both outward and return travel, the latter possibly being the more significant in limiting the lifting of particles away from the surface. According to experimental work done by Moeyersons and DePloey (1976), following the impact of a 4.2-mm diameter drop, sediment grains were ejected from a drop impact zone about 7 mm in diameter. We reason that litter particles lying within a zone of this size could affect splash processes even though they might not be directly struck by the impacting water drop or be ejected by the impact. Further research is required in order to investigate whether litter may restrict soil splash in this indirect way that is additional to the true protection or 'sheltering' of those parts of the surface that lie directly under litter particles.

However, various factors must be borne in mind when evaluating our results. We were not equipped to examine possible shape instability or oscillation in the falling water drops. This shape instability (drops alternating between oblate and prolate) might have contributed to the variability in experimental results, as oblate drops striking the surface dissipate their kinetic energy over a larger target surface area than do prolate drops, resulting in lower impact pressures and shear stress even for the same fall height (Nearing and Bradford, 1987). The test sand was well-sorted, not cohesive, and in the size range that is known to be most readily splashed by water drop impact (e.g., Mazurak and Mosher, 1968). Thus, our absolute sand splash results would not accord with those of ordinary dryland soil materials, that might for example be stabilised by networks of cyanobacterial filaments (e.g., Belnap and Gardner, 1993) and other microphyte growth forms. Here again, additional experiments are needed in order to explore ways in which litter mobility may be modified in the presence of biological crusts. Finally, in windy conditions, not all drops released from desert shrubs would be in the ordinary size range for gravity drops. Smaller drops shaken off under these conditions would result in much lower stresses at the surface. Though smaller drops might be ineffective in sand splash, they might nonetheless contribute to the outward displacement of litter from beneath shrubs, which we suggest is a potentially important early stage in the modification of shallow sheetflow across low-gradient desert landscapes. Further experimental work would be required to assess the minimum drop size and fall height required to mobilise litter particles. Nonetheless, it is clear from the preliminary experiments reported here that plant litter is both mobile and plays a potentially significant role in modifying splash detachment and transport in dryland environments. The presence of litter may well result in a diminution of the outward splash of mineral particles from beneath dryland shrubs, so contributing to the plant mound microtopography that is common in desert shrublands, and which in turn has significant effects on the path and behaviour of surface runoff.

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