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SHORT COMMUNICATION

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Lake survival of hatchery-reared adfluvial brown trout—A case study in a large natural lake in Sweden

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Abstract

Throughout their native range, adfluvial brown trout populations have declined due to habitat degradation and over exploitation. As a consequence, numerous restoration projects that include stocking of hatchery-reared trout have been conducted; however, estimates of survival in large lakes remain scarce. Here, we use telemetry to evaluate the survival of stocked trout smolts and sub-adults in a large lake in central Sweden. Of the smolts released in the main tributary, 42% entered the lake. Both life stages suffered high rates of mortality. Only 8% of smolts survived the first 10 months after entering the lake and 10% of those released as sub-adults survived 23 months post-release. In agreement with studies on anadromous trout, we conclude that stocking of hatchery-reared individuals is not an efficient method to recover population numbers due to poor performance in the wild. Similar studies from other large lakes and comparisons with wild conspecifics would increase the applicability of the results and promote further understanding of the utilization of hatchery-origin trout to rebuild wild populations and sustain fisheries.

KEYWORDS
acoustic telemetry, mortality, *Salmo trutta*, Siljan, Smolt, sub-adult

1 | INTRODUCTION

Throughout their native range, brown trout (*Salmo trutta* L.) inhabit numerous freshwater lakes that contain extensive pelagic habitat and commonly use tributaries for spawning (Ferguson et al., 2019). Like other populations of brown trout, adfluvial populations have declined due to habitat degradation, anthropogenic barriers, and harvest (Bergman et al., 2014). As a consequence, numerous restoration projects, which often include stocking hatchery-origin brown trout, have been initiated to increase population numbers in support of conservation and fisheries objectives. In such stocking programs, information on the survival of stocked brown trout in lakes is crucial for proper evaluations and to be able to maximize effectiveness. Stocking of smolts in streams entering lakes is one of the most common methods applied to restore natural runs and support fisheries. However, to provide immediate fishery opportunities and avoid high mortality rates at early life stages, release of brown trout at the sub-adult life stage directly into lakes has also been conducted. For both anadromous and freshwater populations of brown trout, the shift in habitat use that occurs when juveniles leave their natal streams as smolts and enter the open pelagic habitat, represents a major challenge and often results in a high rate of mortality (Thorstad et al., 2016). While the survival of anadromous brown trout has received significant scientific attention during their seaward migration and during their initial marine phase (Atencio et al., 2021; Thorstad et al., 2007) little is known about trout that inhabit large natural lakes, but see Kennedy et al. (Kennedy et al., 2021). This data gap poses a major challenge for projects that stock adfluvial brown trout in large lakes and their tributaries.

To estimate the survival of brown trout smolts and sub-adults in lakes, we used acoustic telemetry to describe the survival of hatchery-reared 2-year-old smolts released in a main tributary, and 3-year-old sub-adults released directly into a large natural lake in Sweden.

2 | METHODS

2.1 | Study site

This study was conducted in Lake Siljan located in central Sweden at lat. 60°50′59.99″ N; long. 14°47′59.99″ E, 160 m above sea level (Figure 1). The lake consists of seven interconnected main basins with no restrictions to fish movement. The catchment size is 11,967 km^2 and the total lake surface area is 345 km^2 with a mean and maximum depth of 28 and 134 m, respectively. The lake has two major tributaries, upper Österdalälven and Oreälven, that have mean discharges of 90 and 22 $m^3\ s^{-1}$, respectively. The outlet of the lake is located at the southernmost basin with a mean discharge of 155 $m^3\ s^{-1}$. As the main tributaries are developed for hydropower, a supplementary stocking program of 2-year-old brown trout smolts and 3-year-old sub-adults has been in place for several decades as mitigation for reduced natural production. Despite the occurrence of dams without fish passage, both hatchery-reared and wild trout migrate upstream from the lake to the major tributaries and spawn downstream of the lowermost dams. The adipose fin of all hatchery-reared individuals has been consistently removed to distinguish the origin (hatchery vs. wild) of caught fish. Approximately 50–100 adult trout of both hatchery and wild origin are annually caught in upper Österdalälven as brood-stock. Eggs and fry are kept under standard rearing conditions until the fry reaches the smolt stage at 2 years of age; thereafter, they are released in May below the lowermost dam of upper Österdalälven (Figure 1). Smolts move downstream to the lake and spend 1–3 years there before returning to the river for spawning. Northern pike (*Esox lucius*) represents the main predator in the system and occurs both in the lake and the tributaries. Brown trout fisheries are predominated by trolling from June through November and the bag limit is one trout per day and the minimum harvest size is 55 cm. Weather conditions generally restrict fisheries to only a few days a month and hazardous ice covers the lake from December to April and is rarely utilized for ice fishing.

2.2 | Fish tagging and release

In 2018, randomly collected Siljan strain hatchery-reared brown trout smolts ($n = 60$) with a total length of 23.5 ± 2.1 cm (mean ± SD) were anesthetized (MS-222), and tagged at the hatchery. An acoustic V7 transmitter (diameter 7 mm, length 19.5 mm, 0.7 g in water, signal delay 120 s, 69 kHz, Innovasea Systems Inc., USA) with an estimated lifespan of 305 days (10 months) was placed in the abdomen through

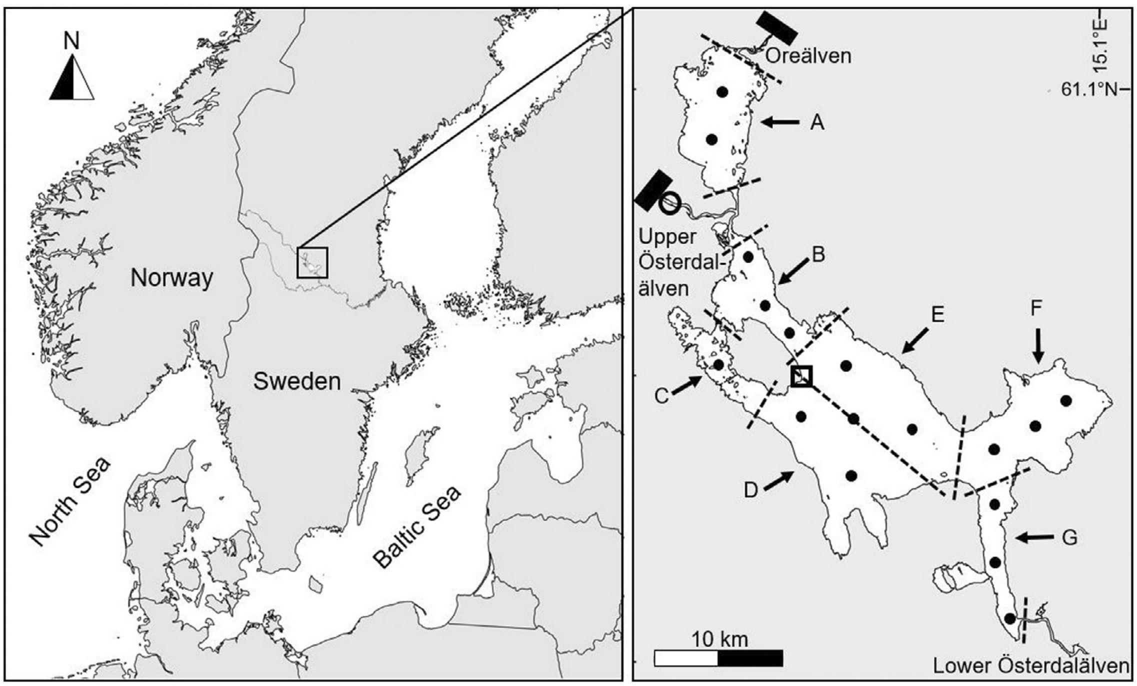

FIGURE 1 Geographic location of Lake Siljan in central Sweden, its main tributaries, upper Österdalälven and Oreälven, and hydropower plants (solid rectangles). Closed circles show location of lake receivers and upper case letters (A–G), and broken lines indicate sub-basin division. Open circle and square indicate the release site of smolts and sub-adults, respectively.

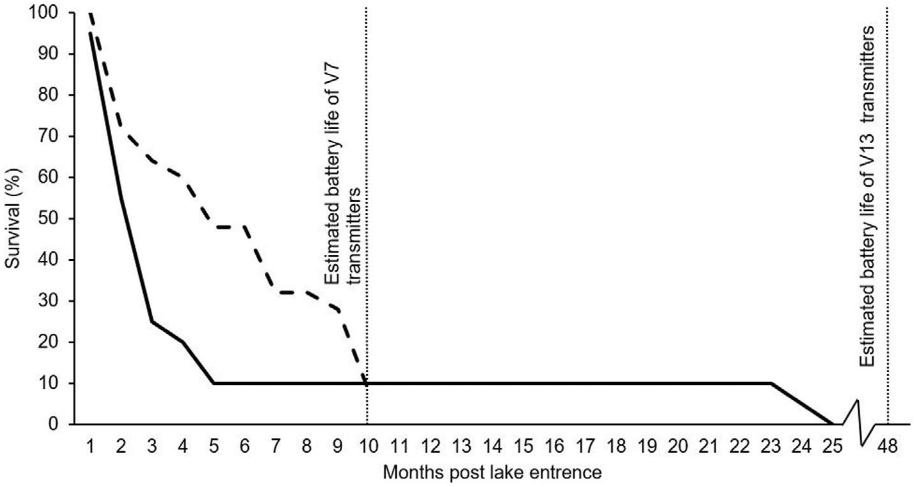

FIGURE 2 Survival of tagged hatchery-reared brown trout smolts (dashed line) and sub-adults (solid line) after entering Lake Siljan in central Sweden. Smolts were released in a tributary entering the lake and sub-adults were released directly in the lake. Dotted lines indicate estimated battery life of the acoustic transmitters used, 69 kHz V7 and V13 (Innovasea Systems Inc., USA).

a 15-mm incision that was closed with two sutures. After tagging, the fish were kept to recover for 4 days before release on the 23rd of May in the upper Österdalälven below the lowermost dam (Figure 1) together with 15,000 untagged smolts of equal age and size to mimic long-term standard stocking procedures and post stocking conditions for the fish at the site. In addition, randomly collected Siljan strain 3-year-old hatchery-reared sub-adults ($n = 20$) with a total length of 41.0 ± 2.7 cm (mean ± SD) were also tagged using equivalent tagging procedure. Due to their larger size, sub-adults were tagged using V13 transmitters (diameter 13 mm, length 30.5 mm, 5.1 g in water, signal delay 120 s) with an estimated maximum lifespan of >1440 days (48 months). Four days after tagging, the sub-adults were released on the 18th of September into the central part of the lake (Figure 1) together with 900 untagged individuals of equal size and age to mimic long-term standard stocking procedures and post-stocking conditions for the fish at the site. No smolts or sub-adults died during the 4-day post-tagging recovery period. Anglers were not informed about the release of tagged brown trout. Due to logistical and economic constraints, we were not able to keep control groups of brown trout in the hatchery.

2.3 | Receiver deployment and survival estimates

Seventeen receivers (69 kHz, Innovasea Systems Inc., USA) were deployed in Lake Siljan (Figure 1). Additionally, seven receivers were deployed in the upper Österdalälven between the smolt release site and the lake. The receivers were placed 2–4 m above the streambed and lake floor using submerged buoys. Receivers were retrieved and redeployed annually for battery change and data offload during the 48-month study period. Survival of smolts that entered the lake and sub-adults that were released directly into the lake represented the main measurable outcome of the study. It was estimated as the time period (months) when movement between receivers was detected. Individuals who were not detected on any receiver or only showed detections at a single receiver for >15 days and no detections at any other receiver post the 15-day period were assumed to be dead (Klinard & Matly, 2020).

3 | RESULTS

Tagged smolts and sub-adults were detected by receivers in the lake during the full period of estimated battery life of smolts (10 months) and for sub-adults (48 months). Twenty-five out of 60 (42%) of the tagged trout smolts released in the river, swam downstream into the lake during the study period. All smolts detected in the lake entered the lake the same month they were released. For the individuals not detected in the lake, the majority (85.7%) were not detected beyond the month of release (May 2018). Only three individuals were considered to be alive in the river through October 2018. The last detection of a live individual in the river was in January 2019. In the lake, tagged smolts swam extensively between all sub-basins except for the northern- (A) and western-most (C) sub-basins (Figure 1). The smolts that entered the lake from the river experienced rapid mortality and only two individuals (8%) survived the entire period of estimated transmitter battery life (10 months post-release) (Figure 2).

Of the total 20 tagged sub-adult trout released in the lake, 19 were detected during the study period. Like the smolts, sub-adults swam extensively between all sub-basins except for A and C. Sub-adults showed a dramatic decline in survival during the first 5 months following release and only two individuals (10%) survived 23 months post-release. No individual survived to the end of the study period, 48 months post-release (May 2022).

4 | DISCUSSION

Consistent with low survival rates reported for anadromous salmonid smolts entering marine environments (Aarestrup et al., 2014; Losee et al., 2019), the smolts in our study suffered high rates of mortality shortly after entering the lake. Regarding survival specifically associated with freshwater lakes, most studies on trout have focused on small artificial lakes, along rivers, that result in delay or exaggerated predation when anadromous trout smolts migrate to the sea (Jepsen et al., 1998; Schwinn et al., 2017). Results from these studies might therefore not fully reflect survival rates occurring in large natural lakes that include vast pelagic habitat. Unfortunately, studies of adfluvial trout smolts and sub-adults during extended periods (i.e., multiple months) in large natural lakes remain scarce, with the exception of Kennedy et al. (2021), who studied trout (<45 cm) of wild origin in a large lake (>100 km^2) in Northern Ireland for a full year. They found that only 5%–10% of the tagged individuals were still actively detected 1 year after tagging, which indicates similar survival to our study. The authors concluded that this noticeable low survival of wild individuals was likely due to substantial predation by northern pike in the lake. In the current study, survival rates were probably lower than what would be expected for individuals of wild origin. Fish of wild and hatchery origin differ in many aspects as a result of different selection mechanisms (Huntingford, 2004). Fish in hatcheries experience a less complex environment; they are provided with food on a fixed schedule—often at large quantities, predators are lacking and diseases are treated. These conditions result in fish poorly adapted to the natural environment and this may have negative implications for the success of stocking programs (Einum & Fleming, 2001). In fact, several studies have documented discrepancies in survival between wild and hatchery-produced trout (Aarestrup et al., 2014; Serrano et al., 2009).

High mortality in hatchery fish could be compensated by increasing the number of stocked individuals. However, in addition to high economic costs, the continual release of a large number of hatchery trout could have negative effects on the native stock as well as other aquatic organisms and the lake ecosystem as a whole (Levin et al., 2001; Pope, 2008).

The majority of smolts released in the river (58%) never entered the lake. Mortality of hatchery-reared fish is often greatest shortly after release due to predation (Jepsen et al., 1998; Kekäläinen et al., 2008) and pike were present in the river in our study. High condition factor and lipid concentrations, common in hatchery-reared fish, have been proposed to contribute to slow migratory performance and predator avoidance for hatchery-reared fish (Lans et al., 2011; Serrano et al., 2009).

This study presents novel data that improve the understanding of stocking program for trout in lakes, but had important limitations worth noting. Some of the individuals that did not enter the lake could either have adopted a stream resident behavior and remained in the river or not yet reached the proper developmental stage for smoltification. In theory, these fish could have smoltified in the following years, but due to battery lifetime, this could not be monitored within this study. However, only one individual was assumed to be alive in the river 8 months post-release suggesting this was probably not an important factor influencing the results. Furthermore, due to the deployment of receivers in the pelagic parts of the lake, individuals that only used shallow littoral habitat might have remained undetected and would therefore be considered dead. However, as trout are documented to use both pelagic and littoral habitats, it is unlikely that individuals would constantly remain in the littoral zone for 10 months (smolts) or 48 months (sub-adults) which was the battery life of the transmitters used. Owing to our assumption that individuals were still alive as long as they were continuously detected at different receivers, survival might have been overestimated as potential predators carrying tagged individuals in their stomachs could have caused continuous detections at different receivers. However, given the high rate of gastric evacuation of northern pike (Diana, 1979) which is the main predator in the lake, this would not be expected to influence our results significantly. Tagged trout might also have suffered mortality from fishing. However, as tagged trout were considerably smaller than the minimum allowable harvest size limit (55 cm), it is unlikely that the rates of harvest of tagged trout by anglers were significant. Potentially, the tagging procedure might have caused increased mortality of tagged fish (Cooke et al., 2011). Given the size of the tagged fish, mortality did probably not increase by more than c. 10% (Welch et al., 2007). Regardless, mortality associated with tagging would not change the conclusion of the study.

We observed low survival of stocked trout, however a small fraction may survive for multiple years. This is supported by the fact that stocked trout are regularly caught as mature adults in the brood-stock fishery in our study system. It is plausible that these individuals have adopted behaviors similar to those of their wild conspecifics and could, from a behavioral point of view be considered naturalized. How often this occurs and how long it takes for the plastic response to manifest is likely dependent on a combination of environmental factors and the extent of the behavioral mismatch of the stocked population. The higher the mismatch the lower the frequency of adaptive plastic responses would be expected. However, to our knowledge, this has not been studied in stocked fish populations. Alternatively, these surviving trout could represent the part of the behavioral distribution, of stocked fish, that are most similar to the wild type and as such be better prepared for a life in the wild and hence suffer a lower mortality compared to their stocked conspecifics. These fish would be behaviorally indistinguishable from wild fish and as such could be considered a wild behavioral type. Behavioral patterns that promote long-term survival in hatchery-reared fish probably include efficient antipredator behavior as well as optimal use of lake basins for feeding. Comparing the behavior of hatchery-reared individuals that have survived for several years to the behavior of wild individuals is a topic ripe for research that would increase knowledge of long-term interactions between wild and hatchery-reared fish.

Given the existing anthropogenic stress on freshwater ecosystems and the associated decline in fish abundance (Young et al., 2016), there is an increased need for evaluations of stocking programs to understand their role in fisheries management. Empirical data from additional lakes and species would be valuable as stocking programs are a popular, cost-effective management strategy to aid threatened fish populations (Marsh et al., 2005). Given the potential negative effects of stocking on genetic diversity and fitness, the stocking genotype and location should be carefully considered (Christie et al., 2012; Einum & Fleming, 2001). Our results on the survival of trout introduced at different stocking locations and life stages provide important insights for fisheries managers initiating stocking programs. Similar studies of stocked trout from other large lakes are encouraged as they would test the applicability of these results to other systems and geographic areas.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

Aarestrup, K., Baktoft, H., Koed, A., Villar-Guerra, D., & Thorstad, E. (2014). Comparison of the riverine and early marine migration behaviour and survival of wild and hatchery-reared sea trout *Salmo trutta* smolts. *Marine Ecology Progress Series*, *496*, 197–206.

Atencio, B. J., Thorstad, E. B., & Jensen, J. L. A. (2021). Keeping close to the river, shore and surface: The first marine migration of brown trout (*Salmo trutta*) and Arctic charr (*Salvelinus alpinus*) post-smolts. *Journal of Fish Biology*, *99*, 462–471.

Bergman, E., Norrgard, J. R., & Hart, P. J. B. (2014). Atlantic Salmon and Brown trout in Lake Vanern: A proposal for a co-management system. *Aquatic Ecosystem Health & Management*, *17*, 365–373.

Christie, M. R., Marine, M. L., French, R. A., Waples, R. S., & Blouin, M. S. (2012). Effective size of a wild salmonid population is greatly reduced by hatchery supplementation. *Heredity*, *109*, 254–260.

Cooke, S. J., Woodley, C. M., Brad Eppard, M., Brown, R. S., & Nielsen, J. L. (2011). Advancing the surgical implantation of electronic tags in fish: A gap analysis and research agenda based on a review of trends in intracoelomic tagging effects studies. *Reviews in Fish Biology and Fisheries*, *21*, 127–151.

Diana, J. S. (1979). Feeding pattern and daily ration of a top carnivore, the northern pike (*Esox lucius*). *Canadian Journal of Zoology*, *57*, 2121–2127.

Einum, S., & Fleming, I. A. (2001). Implications of stocking: Ecological interactions between wild and released salmonids. *Nordic Journal of Freshwater Research*, *75*, 56–70.

Ferguson, A., Reed, T. E., & Prodohl, P. A. (2019). Anadromy, potamodromy and residency in brown trout *Salmo trutta*: The role of genes and the environment. *Journal of Fish Biology*, *95*, 692–718.

Huntingford, F. A. (2004). Implications of domestication and rearing conditions for the behaviour of cultivated fishes. *Journal of Fish Biology*, *65*, 122–142.

Jepsen, N., Aarestrup, K., Okland, F., & Rasmussen, G. (1998). Survival of radio-tagged Atlantic salmon (*Salmo salar* L.) and trout (*Salmo trutta* L.) smolts passing a reservoir during seaward migration. *Hydrobiologia*, *371*(372), 347–353.

Kekäläinen, J., Niva, T., & Huuskonen, H. (2008). Pike predation on hatchery-reared Atlantic salmon smolts in a northern Baltic river. *Ecology of Freshwater Fish*, *17*, 100–109.

Kennedy, R. J., Rosell, R., & Allen, M. (2021). Some observations on the behaviour of lake-dwelling brown trout in lower Lough Erne. *Biology and Environment: Proceedings of the Royal Irish Academy*, *121B*, 1–8.

Klinard, N. V., & Matly, J. K. (2020). Living until proven dead: Addressing mortality in acoustic telemetry research. *Reviews in Fish Biology and Fisheries*, *30*, 485–499.

Lans, L., Greenberg, L. A., Karlsson, J., Calles, O., Schmitz, M., & Bergman, E. (2011). The effects of ration size on migration by hatchery-raised Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*). *Ecology of Freshwater Fish*, *20*, 548–557.

Levin, P. S., Zabel, R. W., & Williams, J. G. (2001). The road to extinction is paved with good intentions: Negative association of fish hatcheries with threatened salmon. *Proceedings of the Royal Society B: Biological Sciences*, *268*, 1153–1158.

Losee, J. P., Kendall, N. W., & Dufault, A. (2019). Changing salmon: An analysis of body mass, abundance, survival, and productivity trends across 45 years in Puget Sound. *Fish and Fisheries*, *20*, 934–951.

Marsh, P. C., Kesner, B. R., & Pacey, C. A. (2005). Repatriation as a management strategy to conserve a critically imperilled fish species. *North American Journal of Fisheries Management*, *25*, 547–556.

Pope, K. L. (2008). Assessing changes in amphibian population dynamics following experimental manipulations of introduced fish. *Conservation Biology*, *22*, 1572–1581.

Schwinn, M., Baktoft, H., & Koed, A. (2017). A comparison of the survival and migration of wild and F1-hatchery-reared brown trout (*Salmo trutta*) smolts traversing an artificial lake. *Fisheries Research*, *196*, 47–55.

Serrano, I., Larsson, S., & Eriksson, L. O. (2009). Migration performance of wild and hatchery sea trout (*Salmo trutta* L.) smolts—Implications for compensatory hatchery programs. *Fisheries Research*, *99*, 210–215.

Thorstad, E. B., Økland, F., Finstad, B., Sivertgård, R., Plantalech, N., Bjørn, P. A., & McKinley, R. S. (2007). Fjord migration and survival of wild and hatchery-reared Atlantic salmon and wild brown trout post-smolts. *Hydrobiologia*, *582*, 99–107.

Thorstad, E. B., Todd, C. D., Uglem, I., Bjørn, P. Å., Gargan, P. G., Vollset, K. W., Halttunen, E., Kålås, S., Berg, M., & Finstad, B. (2016). Marine life of the sea trout. *Marine Biology*, *163*, 47.

Welch, D., Batten, S., & Ward, B. (2007). Growth, survival, and tag retention of steelhead trout (*O. mykiss*) surgically implanted with dummy acoustic tags. *Hydrobiologia*, *582*, 289–299.

Young, H. S., McCauley, D. J., Galetti, M., & Dirzo, R. (2016). Patterns, causes, and consequences of Anthropocene defaunation. *Annual Review of Ecology, Evolution, and Systematics*, *47*, 333–358.

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