Principles of sustainable land-use systems developed and evaluated by the Munich Research Alliance on Agro-Ecosystems (FAM)

Prinzipien einer nachhaltigen Landnutzung – Vorstellungen und Erfahrungen des Forschungsverbundes Agrarökosysteme München (FAM)

1. Introduction

Agriculture of the future has to meet two challenges. (1) Farming has to be economically sound and productive to ascertain a sufficient supply with agricultural products. (2) To maintain this productivity and to enforce peoples’ health and welfare, future land use has to be sustainable. This second goal can only be reached by protecting resources.

Agricultural ecosystems depend on biotic and abiotic resources. Among abiotic resources, present management causes remarkable soil compaction (Voorhees...
1992), soil erosion (Agassi 1995, Bork 1988), eutrophication and pesticide pollution (Cooper 1993). Future agriculture has to reduce these loads to tolerable levels. Most of the organisms comprising the biotic resources do not affect crop yields negatively and some of them even have positive effects. Nevertheless, the intensification of farming during the last decades has severely decreased species diversity (Korneck & Sukopp 1988, Blar 1993).

A representative segment of a mainly arable landscape facing all mentioned problems of resource deterioration was re-designed and principles of sustainable land use were consequently set into practice. The area was split between an integrated and an organic farm to show that these principles can be applied even under greatly contrasting management systems.

Many of the problems mentioned above result from deficiencies in the understanding of agro-ecosystems. Traditional research is characterized by a discipline approach which hardly takes into account interactions (Auerswald & Kutilek 1998). Whereas ecologists or soil scientists, for instance, are well aware of sitespecific differences, they often neglect economic or social constraints. On the other hand, economists often neglect site properties. The behavior of agro-ecosystems can only be understood in a holistic research which integrates the different disciplines. The FAM Research Alliance applies such an integrated research to study the fluxes that determine agro-ecosystems. The fluxes studied are (1) energy fluxes of global radiation as well as from fuel, (2) water and matter fluxes by natural and farming processes, (3) information fluxes like the spreading of genomes, or of agricultural knowledge, and (4) money fluxes which drive agricultural systems. Many of these fluxes are hardly detectable in systems under equilibrium-flux conditions. Land-use changes cause imbalances and open the opportunity to study these fluxes while the agro-ecosystem approaches a new equilibrium. Here, we will use the long-term (8 years) results to determine whether the landscape re-design and the principles of a sustainable agriculture reduced the biotic and abiotic problems and improved economic returns. Recommendations stemming from this type of research should help to solve the different problems simultaneously, instead of leaving the farmer with a diversity of often contradicting recommendations to solve each of the problems individually.

2. Material and methods

2.1. The research site

The “Tertiärhügelland” (Tertiary Hill Country) of southern Bavaria is an important agricultural landscape comprising about 30% of the arable land of Bavaria. Characteristic features are considerable gradients of soil properties (e.g., differences in clay content of > 50% over < 100 meters’ distance) and marked differences in relative relief (Sadowski & Auerswald 1999). This landscape is severely confronted with all the problems of modern intensive agriculture such as deterioration of soil and water quality as well as species diversity. A typical part of that farmland, 114 ha in size (Fig. 1), was leased near Scheyern, about 40 km north of Munich.

Before FAM took over, most of the study area was managed by the Scheyern Benedictine Abbey agricultural administration. Their main concern was arable farming. Cash crops such as wheat, barley and oil seed rape were the most frequent crops. Grassland was formerly leased or stocked with cattle belonging to other farmers. The FAM project started in November 1990. During an inventory phase, all fields were cultivated equally with winter wheat in 1991 and with spring barley in 1992 to level out starting conditions on the different fields and to determine soil and crop growth properties on the entire arable land with high resolution under comparable conditions (Auerswald et al. 1997). Following harvest in autumn 1992, the second and main phase of the project was started by redesigning the area and by separating it into two distinct management systems (Fig. 1, right side). One system corresponds to the principles of integrated farming, covering an area of 46 ha. The other system is 68 ha in size and follows the rules of the German Association for Ecological Farming (AGÖL). The crop rotation of the integrated system consists of potato, winter wheat, maize and winter wheat. On the organic farmland grass-clover mixture, potato, winter wheat, winter rye, white lupine, and sunflowers are cultivated in rotation.
The organic farm runs a herd of 30 suckler cows with one bull on the grassland and spreads manure from the winter shed, while the integrated farm feeds maize to 49 steers and applies slurry manure.

2.2. The land use principles

Landscape design: Soil use has to be site-specific. Due to the small-scaled variation in soil and slope properties, the field size was decreased to allow for site-specific management (Fig. 1). This is regarded to be superior to the so-called precision farming on large fields, because not only agrochemicals can be used site-specifically, but also the timing of management operations can be optimized. To compensate for the additional time needed for cultivating small fields, their layout was improved. While the initially large fields had up to 19 corners, the new field layout mainly has rectangular fields with widths optimized for the operating width of the field machinery. Site properties always vary more along the slope than along the contour. In our research area, geostatistical analysis of soil properties (Auerswald & Sinowski 1999) has shown that soil varies about twice as much along the slope than along the contour line. Homogeneity of the fields is therefore increased by extending the fields along the contour and decreasing their length along the slope. This will also lower soil erosion as the field borders are designed to divert runoff. The decrease in field size, the abandonment of narrow-angled field corners and of sites unsuitied for arable use increased the amount of border structures and the set-aside areas in the landscape (Fig. 2). The unused land extended to 28.5% in the integrated and to 13.5% in the organic management area. This may provide space for species which cannot survive in intensively managed areas. It also allows to install structures to compensate for undesirable off-site effects which may occur even under the best arable soil use. Grassed waterways were established where frequent ephemeral gullying had made cropping uneconomical, although rich colluvial soils are found in these depressions (Penl et al. 1999). In contrast to conventional grassed waterways (Chow et al. 1999), the erosion-reducing soil use on the arable fields allowed to dispense of maintenance of the waterways, thus to enable vegetation succession and to improve infiltration, sediment retention and species diversity. Small retention ponds with underground tile outlets dampen runoff and retain sediment (Weigand et al. 1995). Buffer strips along the creeks reduce direct agricultural influence on the water bodies. Deadwood pilings (Auerswald & Weigand 1996) on unused land provide material for organisms depending on dead wood, provide shelter and resting places for many animals and will develop into living hedges by the upcoming of authochthonous bushes and trees.

Cropping practice: The main principle is that the soil has to be kept covered as long as possible, preferably with growing plants or with plant residues where this is not possible. This will lower nitrate leaching and erosion and increase the input of organic matter into the soil food chain. While the crops are already optimized in this respect by conventional agriculture to increase yields, the period beginning with the opening of a crop, already before harvest, and ending when the new crop is sown, offers a great potential for soil improvement and water protection. This was done by applying mulch tillage (Kainz 1989), even with potatoes, and by sowing undercrops. To increase mulch tillage, row crops were introduced, thereby also improving economic returns. Sowing of undercrops improves nitrogen supply and soil protection especially in the organic farming system. Unconventional methods were applied: mustard was sown into potato fields, for instance, when the potato-leaf cover decreased due to a Phytophthora infestans infection (Kainz et al. 1997). This provided cover and extracted nitrate from the soil until the potatoes were harvested.

The almost continuous soil cover can only be maintained if tillage is reduced. Soil compaction even close to the surface has then to be avoided by using the lightest machine for a given task and by the consequent use of ultra-wide tires on all farming machinery. Onland plows which allow to run with both wheel tracks on the unpiowed land, shallow tillage depth, non-inverting tillage and stabilization of the soil structure by increasing biological activity further assist this concept. Sods in rotation are helpful to stabilize soil aggregates (Wischmeier & Smith 1978) especially under organic farming where the more frequent tillage for weed control weakens aggregates (Kaeufler 1999).

To reduce soil compaction further and to increase economic returns, all unnecessary operations are
avoided. Mineral P and K fertilizers are not used because of the large supply by the soils themselves and the little net loss from the farm by the goods sold (WEINFURTNER 2000). Liming was also reduced compared to common recommendations (AUERSWALD et al. 1996) and the amount of N fertilizer could be reduced due to the N-conserving plant cover.

2.3. Measuring methods

In order to gain representative results of the management-induced changes, a 50 by 50 m grid of more than 400 reference points was fixed over the experimental area. There, soil properties, nutrient contents, water regime, crop yields and variables describing vegetation and fauna are measured. In addition, stations monitoring surface and groundwater runoff and measuring the climatic conditions complete the program. For details of methods see PFADENHAUER et al. (1996) and LÜTZOW et al. (1998).

3. Results

3.1. Soil protection in agricultural land use

Soil compaction: The measures taken to reduce over-compaction, namely setting aside shadowed or wet areas, on-land plowing, the use of light-weight machinery, reducing tillage and reducing passes, all helped increase the pore volume, the stability of the soil matrix, and led to a higher infiltration and bearing capacity (ROGASKI et al. 1995). The main component, however is the use of ultra-wide tires even on machinery for which their use is not recommended by the manufacturers (Fig. 3).

Erosion: Soil loss at an average rate of 9.1 t ha⁻¹ a⁻¹ was estimated to have occurred before the land use had been changed. This is high above the local soil-formation rate of 1 t/ha-a. It could be reduced mainly by setting aside land on steep sites, the creation of field borders on the contours and ditches to stop runoff, establishment of grassed waterways and green fallow strips along the water bodies. These options of landscape design contributed about 58% to the reduction of soil loss (PFADENHAUER et al. 1997).
Within the arable fields an almost continuous cover of at least 50% with green or dead plant material was achieved, which shielded the soil against the erosivity of the rains (Fig. 4). Under improved integrated farming, the mustard sown as catch crop for mulch tillage, and the plant residues were essential to supply cover between the cash crops which leave long gaps in the cover. Under improved organic farming, this was achieved by underseeding of an alfalfa-clover-grass sod or a catch crop. Only potatoes still leave some critical periods in both systems. Conventional farming would have had soil cover mainly by cash crops, exposing the soil to the rain impact over long periods.

This almost continuous soil cover prevented sealing by rain and increased infiltration by about 30% (SCHRODER & AUERSWALD 2000) and reduced soil detachment and runoff transport capacity. This decreased erosion by approx. another 42% (PFADENHAUER et al. 1997). In total, all land-use changes caused soil erosion by water to drop by at least two orders of magnitude to an average of approximately 0.05 t/ha·a over the entire area (Fig. 5). Along with runoff and sediment reduction, P-transport was reduced to one twentieth. On steep slopes, which were tilled perpendicular to the contour lines, translocation by tillage implements, esp. by plow, even exceeded water erosion. By setting aside the steepest slopes (> 0.3 m/m) and reducing depth and frequency of soil tillage the translocation rates dropped as well.

Nitrate: The extended period of a plant cover due to the catch crops reduced soil nitrate drastically. This is especially important for the organic farms because of its N limitation. Using mustard as a catch crop after chaffing the potato foliage to control Phytophthora infestans in late July, and the potato harvest in early September helped to save about 50 kg/ha·N in the mustard, which would otherwise have been leached. Furthermore it helped to suppress weeds, also critical in organic farming (Fig. 6). Similar results were obtained with catch-crop mustard on the integrated farm, which effectively removed nitrate from the soil during the winter leaching period (Fig. 7). Leaving the mustard biomass on the soil surface during mulch tillage restricts its microbial degradation and thus conserves N after the mustard has frozen down during winter. Incorporation into the soil

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**Fig. 5** Runoff, soil loss and particulate phosphorus loss on the FAM experimental station in Scheyern, averaged over 15 small watersheds of 0.5–16 ha in size, with continuous monitoring of Abfluss, Bodenabtrag und partikulärer P-Abtrag im Mittel von 15 denkbaren Kleinflächen (0,5–16 ha Größe) auf der Versuchsstation Klosterneuburg Scheyern

<table>
<thead>
<tr>
<th>Year</th>
<th>Runoff [l/m²-yr]</th>
<th>Soil loss [g/m²-yr]</th>
<th>Particulate P [mg/m²-yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before 1993</td>
<td>52</td>
<td>960</td>
<td>190.0</td>
</tr>
<tr>
<td>1993</td>
<td>30</td>
<td>170</td>
<td>13.0</td>
</tr>
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<td>1994</td>
<td>32</td>
<td>17</td>
<td>2.0</td>
</tr>
<tr>
<td>1995</td>
<td>9</td>
<td>2</td>
<td>0.4</td>
</tr>
<tr>
<td>1996</td>
<td>11</td>
<td>8</td>
<td>2.0</td>
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<tr>
<td>1997</td>
<td>3</td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>1998</td>
<td>15</td>
<td>25</td>
<td>3.0</td>
</tr>
</tbody>
</table>

**Fig. 6** Nitrogen conservation in weeds and mustard between chaffing of the potato foliage (on the 24. July) and potato harvest (on the 11. Sept.), for organically farmed plots with and without mustard sown as catch crop after chaffing, Stickstoffkonservierung im Linkraut und im Senf zwischen dem Abschleppen des Kartoffelkrautes am 24. Juli und der Kartoffelentfernung am 11. September auf Parzellen des organischen Landbaums mit und ohne Zwischenfrucht-Senfanzucht nach dem Abschleppen

**Fig. 7** Average nitrate content at 0–90 cm depth after winter wheat with conventional and with mulch tillage

Mittlerer Nitratgehalt in 0–90 cm Tiefe in Feldern nach Winterweizen bei konventioneller bzw. Mulchausnutzung
would release N rapidly. Even during winter, half of the N fixed in fresh biomass will be mineralized 20 days after incorporation into the soil (Jimenez 1999).

Summarizing, the investigations on the FAM research area have shown that the integrated use of different control methods can reduce soil compaction, overland runoff, erosion and nutrient release simultaneously to an ecologically sound level under Central European climatic conditions, even in sloping areas with intensive agriculture and a pronounced short-distance variation in soil properties. Furthermore, this soil management regime may contribute to enhanced drinking water quality, to increased below- and above-ground species diversity (Beeke & Filser 1998), and to a more efficient use of energy.

3.2. Development of species diversity

On the scale of grid points, the number of species significantly increased under most land-uses (Fig. 8) while the diversity on the farm scale remained nearly constant. There, species numbers increased from 279 in the preliminary phase to only 289 in 1997 (Fig. 9). This indicates species dispersal within the farm. The exchange with other farms, however, was limited (Albrecht & Matthes 1996, Albrecht & Forster 1996, Albrecht & Pilgram 1997). This is not surprising at a level of more than 250 species, and because the exchange of material with other farms is kept small to avoid introduction of pests. Experience with birds shows that mobile species can make use of the new diversity in site conditions. Birds increased from 4 to 7 species and from 48 to 74 nesting pairs right after changing landscape design and cropping practices (Agricola et al. 1996).

Most of the plant species which are regarded to be endangered were found in arable fields (Albrecht et al. 2000). Such species increased at 49 and decreased at 18 grid points in the organic-management fields. This significant increase seems to be caused by the low efficacy of mechanical weed control in contrast to the former herbicide use. Not all of the rare species responded to these improved living conditions with an increase of their habitat size. Veronica triphylla, e.g., is adapted to sandy soils by rapid development in spring, before summer drought limits its growth (Cremer et al. 1991). Although there are other potential habitats in the study area, it constantly occupies only one of them. The reason for this constancy may be a lack of natural strategies for long-distance dispersal, and unfavorable conditions for spreading by human activities. Plants ripen and die long before harvesting machinery can incorporate their seeds into straw or crop seeds. Potential dispersal agents that remain are soil-working implements and wheels of arable machinery. Dispersal experiments (Mayr et al. 1998) showed that the amount of soil adhering to them is so low that transport to other favorable sites is unlikely. In the integrated-management system, rare species decreased at 22 points and increased at only 11 points. The decrease of rare species, despite the significant increase in total plant numbers per grid point, may have been caused by rare weeds suffering more than other plants from the ef-

<table>
<thead>
<tr>
<th>Soil use</th>
<th>Number of samples</th>
<th>species 1992</th>
<th>species 1997</th>
<th>Significance of change</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Arable fields</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organic</td>
<td>129</td>
<td>17</td>
<td>32</td>
<td>***</td>
</tr>
<tr>
<td>Integrated</td>
<td>129</td>
<td>19</td>
<td>19</td>
<td>n.s.</td>
</tr>
<tr>
<td><strong>Set-aside land</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Former arable</td>
<td>26</td>
<td>18.5</td>
<td>39.5</td>
<td>***</td>
</tr>
<tr>
<td>Former grassland</td>
<td>12</td>
<td>20</td>
<td>23.5</td>
<td>n.s.</td>
</tr>
<tr>
<td><strong>Organic grassland</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seeded</td>
<td>29</td>
<td>19</td>
<td>28</td>
<td>***</td>
</tr>
<tr>
<td>Pastures</td>
<td>42</td>
<td>25.6</td>
<td>32</td>
<td>***</td>
</tr>
<tr>
<td>Meadows</td>
<td>25</td>
<td>28</td>
<td>40</td>
<td>***</td>
</tr>
<tr>
<td><strong>Boundary structures</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New</td>
<td>6</td>
<td>20</td>
<td>30</td>
<td>n.s.</td>
</tr>
<tr>
<td>Enlarged</td>
<td>8</td>
<td>24</td>
<td>31</td>
<td>n.s.</td>
</tr>
<tr>
<td>Old</td>
<td>6</td>
<td>35</td>
<td>32</td>
<td>n.s.</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>412</td>
<td>20</td>
<td>30</td>
<td>***</td>
</tr>
</tbody>
</table>

* *** = significant at 99.9% probability, n.s. = not significant
The use of herbicides that became necessary with the increase in weed numbers (ALBRECHT & MATTHIES 1998).

In summary, the creation of set-aside land and boundary structures, as well as the improved organic farming increased small-scale biodiversity and living conditions for rare species. Consequently, both measures can be recommended for the restoration of intensively used agricultural landscapes. Despite the improved establishment conditions on the grid-point scale, the overall number of species did not increase. Therefore, if we want to promote species distribution in agricultural landscapes, strategies to intensify the exchange of species between farms have to be applied. Moreover, the investigations in the development of rare weeds give evidence that even species of normal farmland can suffer from habitat fragmentation and the lack of dispersal facilities on the time-scale tested. Targeted measures like seeding or implanting soil seem to be necessary to pass over these barriers.

### 3.3. Site-specific economic evaluation

One of the most important parameters to evaluate the efficacy of management systems in conventional economic analysis is their average yield, independent of site-specific differences. Common experience, however, shows that yield as well as the variable costs for tillage, fertilizing and pest control vary with sites. A site-specific calculation of economic returns revealed that on many sites costs were higher than the returns from the products sold. Cultivation of these areas thus decreased the net income, and the labor spent for the cultivation of the area is lost for a more thoroughly land care on the other sites. An example is given in Figure 10. A steep field, which had been turned into arable land twenty years ago, caused a net loss of income of 255 DM/ha·yr because of low yields and high costs for traction, harvesting and tire wear on the steep positions on which many operations could only be carried out downslope. The losses of income add up to 4,110 DM/ha for the 20-year period. Furthermore, the arable land-use on the steep slope had induced an average soil loss of >100 t/ha·yr, as could be quantified by the radiotracer technique (SCHIMMACK et al. 2000). Taking into account the nutrient loss alone associated with this soil loss, this amounts to another 1,566 DM/ha·yr or 31,320 DM/ha over the 20-year period. Similar results can be obtained for most of the other areas where agriculture causes severe environmental problems, such as those with poor sandy soils, wet soils, or soils in slope depressions were ephemeral gullying is likely to occur. Hence, environmental quality and economic benefits could both be significantly improved by taking these areas out of arable or even completely out of agricultural use. It is thus not surprising, in spite of 14% of the area set aside in the integrated and 28% in the organic system, that the economic situation significantly improved in both systems. The set-aside area can then serve for purposes which are difficult to fulfill on farmland with its frequent disturbance by man. Modern GPS-supported high-resolution mapping of yields (AUERNHAMMER et al. 1994) offers an easy tool to determine the areas which should preferably be taken out of production. Economic calculations based on these high-resolution maps reveal areas with a net loss of income, which, in the case presented in Figure 11, were only caused by poor yields and not by higher expenses. The pattern of areas with a net loss of income were similar over the years. Reliable planning can be based of a several-year average of net income. Considering the amount of money a farmer wants to earn per working hour or the amount of money he would get from a different source of income, not only those areas with negative net return may be taken out of production, but also those areas where net return per working hour is lower than the individual threshold.

The costs were further lowered by reducing the input of agrochemicals to the necessary level. Phosphorus fertilizers are not necessary on most of the agricultural land in Germany, which has received on average a surplus of about 1,200 kg/ha P (AUERSWALD & WEIGAND 1999). The P loss from the research area, averaged over all fields and grassland and over 5 years, was about 10 kg/ha·yr (WEINFURTNER 2000). It will thus last decades until the surplus has been exhausted. Similar reckoning can be done for K, N and liming (AUERSWALD et al. 1996). Again, economic benefits coincide with a relief of the environment by the reduced use of agrochemicals.

In addition, the reduction in tillage intensity and frequency cuts down the costs. This is exemplified for mulch-till potatoes (Fig. 12). Variable production costs and labor demand are low for mulch-till, because plowing and seedbed preparation are not necessary. Conventional tillage causes about 50% higher planting
costs, while the yields are similar for both systems. The environmental benefits of erosion control, improvement of earthworm activity (KAIZ 1989), control of nitrate leaching (Fig. 7), and the reduction of fuel consumption do not cause additional costs, but increase the farm income on the short term. This applies even more for the long term because of the improved sustainability of the land use. The frequently reported additional costs of environment-friendly production are thus often based on a lack of understanding of site-specific processes in crop growth and environmental stresses by the economists. This is best illustrated by the research farm itself. The income had previously been so low that it was even impossible to replace the last already old tractor, while both the organic and the integrated farm are prospering now.

Yields from potato and wheat, which are cultivated in both systems, are about 1/3 lower with organic than with integrated farming. Comparison of sites with similar soils shows that most of this difference goes back to the – on average – poorer soils on the organically farmed part of the research station. A somewhat lower yield remains for the organic system, however. This necessitates a higher price in order to achieve a comparatively even profit margin which can be either paid by the consumers, or by governmental subsidy, or by a combination of both.

4. General conclusions

The re-design of the landscape and the improved concepts of integrated and organic farming assure sustainability of agricultural management. The improved organic system, in combination with the new landscape design, has some advantages concerning species protection. It might conserve even the rare and sensitive species during arable land use. On the other hand, this system works on a somewhat lower level of productivity. Thus, the economic situation will limit the percentage of organically farmed land. It has, however, to be considered that by farming the arable land organically, higher prizes are paid for the meat produced on the grassland, although yield and expenses on the grassland are similar in both systems. The yield and prize of wheat can thus not be judged in isolation. The (eco-)systems approach is hence necessary not only for ecological, but also for economical processes, in order to arrive at a proper evaluation.

The improved integrated management system, in combination with re-designing measures, predominantly succeeded in protecting soil organisms (Beese &
Filser (1998) and non-biotic resources. As the study area is situated in a typical agricultural landscape where highly endangered species scarcely occur, the protection of the abiotic resources seems to be more important for such areas to maintain a high level of productivity. Consequently, when the yield levels reached by conventional farming must be maintained, the concepts applied in the integrated system might be a solution for such landscapes. Nevertheless, concepts should be developed that reduce the decline of rare species to tolerable levels as well.

By applying the principles of landscape design and farming developed by the FAM, the economic and environmental situation were drastically improved. In spite of an intensive propagation of these methods among farmers and others, the adoption by farmers remained limited, however, because of the uncertainties and risks they have to face until they are familiar with the new system (Napier et al. 1986). Governmental incentives to support this adoption of new methods seem to be more helpful for improving the environmental and the economic situation than present subsidies.

Acknowledgments

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