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Effect of pollutant concentrations on growth characteristics of macrophytes in a constructed wetland treating municipal combined sewage

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ABSTRACT

Constructed wetlands (CWs) have been used for contaminated water treatment for more than three decades. However, the ecological effects of the pollutant loading on CWs are not well known. In this study, five wetland plants (*Phragmites karka* (PK), *Typha orientalis* Presl (TO), *Cyperus malaccensis* Lam (CM), *Schoenoplectus mucronatus* (SM), *Hygrophila pogonocalyx* Hayata (HP)) were chosen and three study sites (42 × 42 cm) were used in a CW in Taiwan. The bioaccumulation of vegetation and effects on wetland ecosystem were tested with different pollutant concentrations of municipal combined sewage. The mean concentrations of BOD_5, NH_4-N, and total phosphorus (TP) at the three study sites were 12.1 ≈ 44.3 mg l^{-1}, 3.6 ≈ 19.8 mg l^{-1}, and 0.4 ≈ 1.9 mg l^{-1}, respectively. The results show that higher nutrient concentrations led to higher bioaccumulations of wetland plants, and the amount of biomass are significantly different in each species. The highest growth rate is observed in CM, in 5314 g-biomass (dry weight) m^{-2}. The drying ratio (wet weight/dry weight) increases with the growth of all five species. The conclusion is that the input of nutrients within the polluted water will increase the production of wetland plants, but may possibly decrease the biodiversity due to higher competition around different species at the same time.

Keyword: Constructed wetlands; Wetland macrophyte; Bioaccumulation; Growth rate; Drying ratio

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1. Introduction

CWs have been widely used in treating polluted water from various sources such as contaminated water bodies [1–5], sewage [1,6], cultivation wastewater [7,8], mining wastewater [9,10], and for various pollutants, including nutrients [1,4,11–17], heavy metals [10,18], and microorganisms [19]. They provide satisfactory fruitages with relatively low costs and less maintenance compared to municipal wastewater treatment plants. The extents of removal of pollutants have widely evaluated and reported in literature. However, the ecological effects imposed by the polluted water on CWs are less studied.

In Taiwan, CWs have been used for municipal combined sewage (combine with housing sewage and rainwater) treatment in recent years, but so far the ecological effects of the sewage treatment process on CWs are not well known. The pollutants were retained or removed through physical, chemical, and biological processes. For nutrients, the biological process pertaining to microorganisms and macrophytes and the interaction

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between them have been given growing attention in literature [20]. Besides providing a stage for the metabolism of microorganism, the wetland macrophytes also play a major role in removal of organic contaminants. By blocking the sunlight, releasing oxygen through rhizome-effect, and direct intake of nutrients, the wetland macrophytes have been recognized as a very important part of wetlands [21]. It has also been proven that the removal rate is higher with existence of macrophytes, though varies with different species. The evapotranspiration rate also depends on the types of macrophyte species [6]. The past researches show that there are obvious differences in biomass and elements accumulation by different wetland macrophyte species. Also, a CW with a single dominant species accumulates more biomass than mixed-growth, but the soil organic matter content could not affect up-take of different macrophytes [22].

In general, organic matter and nutrients are the primary pollution constituents of municipal combined sewage. On the other hand, they are also important parts of life-support components to maintain the productivity and biodiversity of wetlands. The pollutant concentrations decrease because parts of them were up-taken by the microorganism and wetland plants in the wetland system [23,24]. But it is difficult to tell whether the effect of these pollutant loadings to the wetland ecosystem is positive or negative. For example, a high organic loading rate might cause a higher productivity and an inhibition. The objective of this research was to evaluate the effect of pollutant loadings on the wetland ecosystem through measuring the growth of wetland macrophytes.

2. Materials and methods

2.1. Site description

The experiment was conducted in Shin-Hai CW (*see* Fig. 1), located in the riparian of the Da-Han River in New Taipei City, Taiwan. Shin-Hai CW was constructed in 2005 by the Environment Protection Bureau of Taipei County for treating municipal combined sewage. The area of the Shin-Hai CW is six hectares with designed capacity of 2300 CMD ($m^3\ d^{-1}$). The CW is composed of five ponds in series. The first three ponds are designed in typical three-stage form suggested by US EPA [25], and the last two are designed mainly for ecological restoration. The total hydraulic residence time of the Shin-Hai CW is about 4 ≈ 5 d.

For the research, three experimental sites (sites A, B, and C) locate in pond 1, 2, and 4 (Fig. 1) were chosen for supplying different pollutants concentration. The concentrations of BOD_5, NH_4-N and TP decrease from Site A to Site C as the water flows through from influent (pond 1) to effluent (pond 5). The water depths of all three selected experimental sites are approximately 10–15 cm, and the soil compositions are very similar. The environmental conditions in each site can be considered as homogeneous.

2.2. Experiment distribution

All experiments in this research were conducted in triplicate. Five original wetland macrophyte species were chosen to compare the growth and accumulation, and harvested three times in a period of 8 mo. There are total 45 samples in each site (5 species × 3 times harvest × 3 triplicate samples). Each sampling area is 0.42 m × 0.42 m contained by a plastic basket buried into soil under water with 5 cm above the surface of soil. The large number of holes on the baskets' vertical sides kept the water condition inside the sampling area similar to outside, so that the pollutant concentrations in the same site were homogeneous. The distribution of sampling area with five macrophyte species and three times of harvest in each site is shown in Fig. 2. The operating conditions were controlled at 15.6 ≈ 32.5°C for solution temperature and 6.2 ≈ 9.0 during experiments.

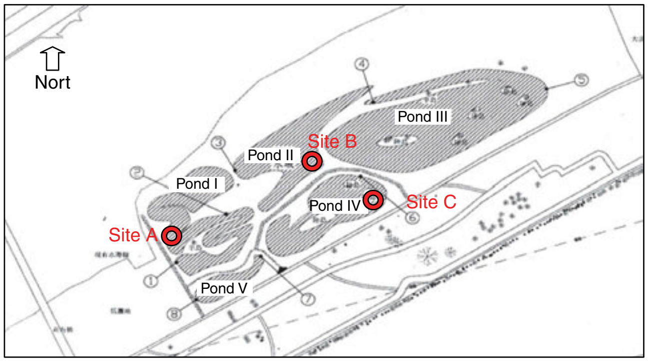

Fig. 1. The schematics of the Shin-Hai CW and the locations of the three experimental sites.

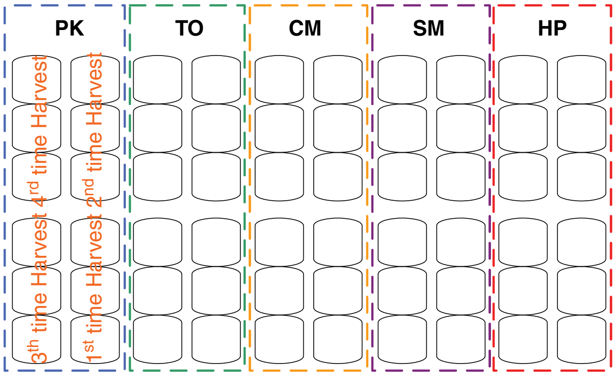

Fig. 2. The distribution of sampling areas in each site.

2.3. Experiment wetland macrophytes

To compare the accumulation ability among different wetland macrophyte species, five original macrophytes species with high potentials of pollution resistance and high growth rates were chosen for the experiment. The species include PK, TO, CM, SM, and HP. PK is one type of reeds (similar to common reed *Phragmites australis*) and TO is one type of bulrushes; the reeds and bulrushes are most frequently used in CWs for polluted water treatment worldwide. The CM and SM are both of *Cyperaceae* with strong fiber tissues but no dormancy, unlike PK and TO. The last one, HP, is the only dicotyledon of the five species and has been protected due to its small wild population and narrow distribution.

2.4. Preparing and planting of the macrophytes

All macrophytes were collected from the Shin-Hai CW region near by the experimental site to ensure good adaptability of the plants to the experimental conditions. After collection, the leaf and stem were cut short and the soils sticking to the roots were cleaned thoroughly. They were then separated into small groups with similar wet-weight (w/w) of about 200 g per each group. Before planting into the baskets, the exact (w/w) were measured and recorded. After measurement, each group was separated into 3 ≈ 4 subgroups, then planted into the sampling areas in early May.

2.5. Sampling and analysis procedure

In this research, the macrophytes were harvested in three harvest times, which are 35 ≈ 40, 120 ≈ 130, and 210 ≈ 220 d after planting, respectively. A primary growth period was allowed to obtain the data of the maximum growth rate. Each harvest in every experimental site was accomplished in two days to collect one set of three samples of all five macrophyte species.

Table 1
The linear regression coefficient of Figs. 6–8

Coefficient of regression $y = a + bx$	BOD		NH_4-N		TP	
	a	*b*	*a*	*b*	*a*	*b*
PK	71.6	31.4	3.7	66.8	89.7	660.6
TO	1496.1	25.0	1323.7	60.8	1419.7	593.0
CM	2222.0	61.7	2128.0	127.5	2301.2	1265.2
SM	2415.0	23.0	2304.7	52.5	2383.6	515.7
HP	786.4	40.6	578.1	93.8	720.2	919.8

When harvesting each sampling area, all plant tissues including the root, stem, and leaf in the plastic basket were dug out first, and then the soils sticked to the roots were cleaned thoroughly. After that, the total height above the soil was recorded and all the tissues were separated into two parts, above ground and below ground, to measure the (w/w) of each portion respectively. The measured tissue was then put into an oven to dry at 105°C for 48 h, and then the dry-weight was recorded.

During the experimental period, the water samples were taken and analyzed once every month for concentration of BOD_5, NH_4-N and TP in accordance with the published methods of US EPA.

3. Results and discussion

3.1. Pollutants concentration

The results of water quality monitoring are shown in Fig. 3. It shows that the concentrations of BOD_5, NH_4-N and TP decrease from Site A to Site C. For BOD_5, the concentration at Site B is about 0.44 times of that at Site A, and the concentration of that in Site C is about 0.55 times of that at Site B or 0.24 time of that at Site A. For NH_4-N, the concentration at Site B is about 0.73 times of that at Site A, and the concentration in Site C is about 0.34 times of that at Site B or 0.25 time of that at Site A. For TP, the concentration in Site B is about 0.69 times of that at Site A, and the concentration at Site C is about 0.28 times of that at Site B or 0.19 times of that in Site A. The differences in concentrations provide the basis of different growing conditions.

3.2. Macrophytes growth

Fig. 4 shows a comparison of the growth rates of all five macrophyte species at three harvest times and

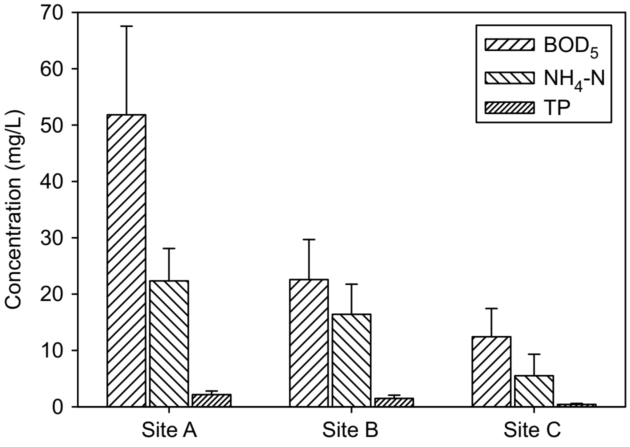

Fig. 3. The comparison of water quality at the three sites.

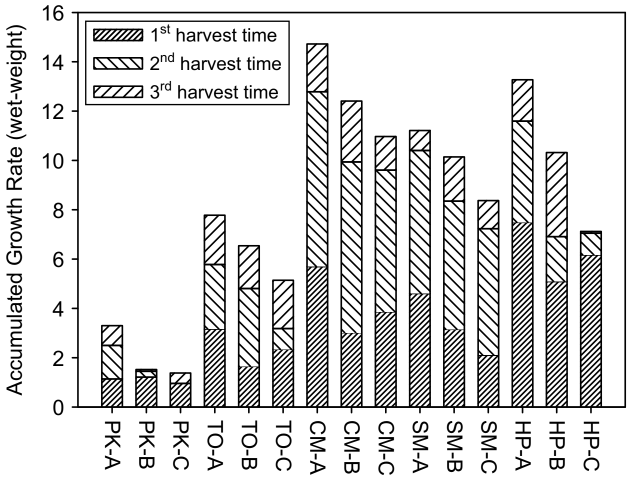

Fig. 4. A comparison of the growth rates of all five macrophytes species at three harvest time and three sites.

three study sites. The growth rate of macrophytes here is defined as a ratio of the final (w/w) (measured right after harvest) divided by the original (w/w) (measured before planted). By definition, the growth rate is a non-dimensional value so that a small difference in original (w/w) will not affect the reliability of the final growth rate value. As shown in Fig. 4, the CM has the highest growth rate and the HP has the lowest growth rate. The growth rates vary among different macrophyte species, indicating that the productivities of different macrophyte species under same water conditions are significantly dissimilar. However, with the decreasing of pollutant concentrations from Site A to Site C, the final growth rates of all five macrophyte species also decrease accordingly. This implies that all macrophyte species grew better in higher nutrient concentrations. However, the growths of all five macrophyte species in the third harvest time are relatively less than those of the previous two harvest times. This shows that the plants might have approached maturation and saturation limits set by space and physiological properties.

According to the distribution of the accumulated growth rate, the five macrophyte species can be divided into three different growth types: infancy growth, middle-stage growth, and uniform growth. HP belongs to the infancy growth type, and most dicotyledonous emerged wetland plants are supposed to be part of this type from field observation. This type of macrophytes grows quicker in the infancy stage (1 or 2 mo) rather than in the later stages. CM and SM are of middle-stage growth type. The growth of plants of this type focus on the middle stage and amount of growth during the middle stage in the three sites of each macrophyte species are almost the same. This means that in the middle growth stage the difference of nutrients concentration does not show significant effect on the growth of the two macrophyte species. The TO belongs to the uniform growth type, the growth during three stages are proportionally the same.

The difference in the growth type of these wetland plant species will potentially affect the harvest strategy used to maintain high pollutant removal efficiency of CWs. Most harvests should be conducted after the harvest time of the highest growth rate to remove the maximum amount of pollutants through harvest management.

3.3. Bioaccumulation

The total dry-weight represents the total bioaccumulation of all macrophyte species at each site. Since the original weight has a significant effect on the final dry-weight, the value of bioaccumulation has been normalized by adjusting the original weight to 200 g per sampling area. It is then divided by the size of sampling area (0.42 m × 0.42 m). Therefore the total amount of bioaccumulation can be expressed in kg m^{-2} with 200 g as the original weight. Fig. 5 shows a comparison of the bioaccumulation. Comparing Fig. 5 with the growth rate in Fig. 4, the CM still has the highest bioaccumulation among the five with 5484 g dry-weight m^{-2} (or 54,840 kg ha^{-1}) in total as well as the highest growth rate. On the other hand, the HP which has the second highest growth rate, but has the third highest bioaccumulation slower than SM. The correlation between the bioaccumulation and the growth rate remains unclear. But the experimental results reveal that the bioaccumulation in the third harvest time of the first four macrophyte species are much higher than the growth rate in the same harvest time. It implies that although the growth rate (in (w/w) base) for all monocotyledons is smaller in the

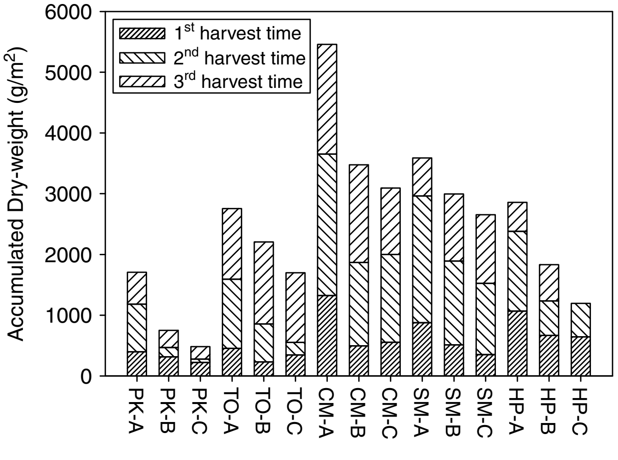

Fig. 5. The biomass accumulation of all five macrophytes species in three experimental sites.

third harvest time, the bioaccumulation (in dry-weight base) could be much more due to the plants change their composition to the tissue part [26,27].

HP is the only dicotyledon of the five and unlike the other four, the bioaccumulation in the last two harvest times are very similar to the growth rate. However, the bioaccumulation in the first harvest time is much lower than the growth rate. It shows that only a few growth or bioaccumulated in the plants tissue in the first harvest time.

Linear regression analysis was used to analyze the increasing tendency of bioaccumulation of different macrophyte species under different pollutant concentrations. Figs. 6–8 show the results of linear regression on bioaccumulation versus pollutant concentration of BOD_5, NH_4-N and TP. Each data point in the figures is the average of three raw values. The standard deviations are also shown in the figures. In Figs. 6–8, the R^2 values range from 0.9983 (PK vs. BOD)–0.7347 (CM vs. NH_4-N). Among all the three indicators, BOD_5 has the highest correlation for all five macrophyte species and all the R^2 values are higher than 0.9. In other words, BOD_5 could possibly be treated as an indicator to access the potential growth ability of wetland macrophytes under different pollutant loadings. If we compare the coefficient *a* (intercept) and *b* (slope) of the linear regression, we can see that SM and CM have the highest *a* and *b* values in all three different pollutants. It implies that CM can accumulate biomass the fastest and has the best response to advance the bioaccumulation rate when the pollutant concentration increases.

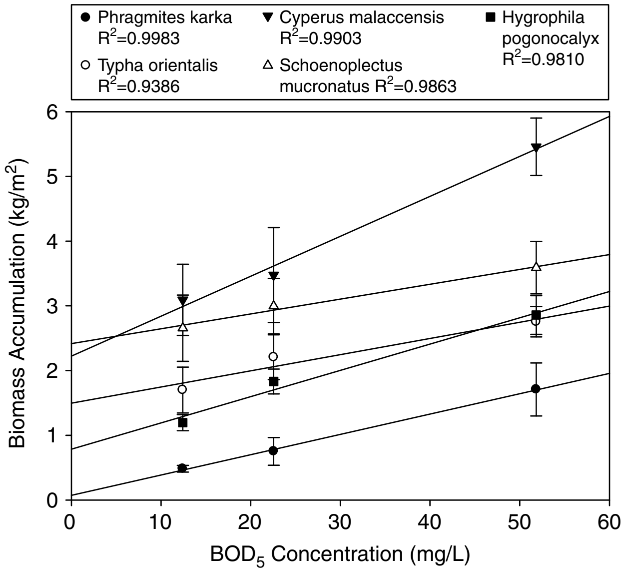

Fig. 6. The linear regression on the biomass accumulation versus BOD_5.

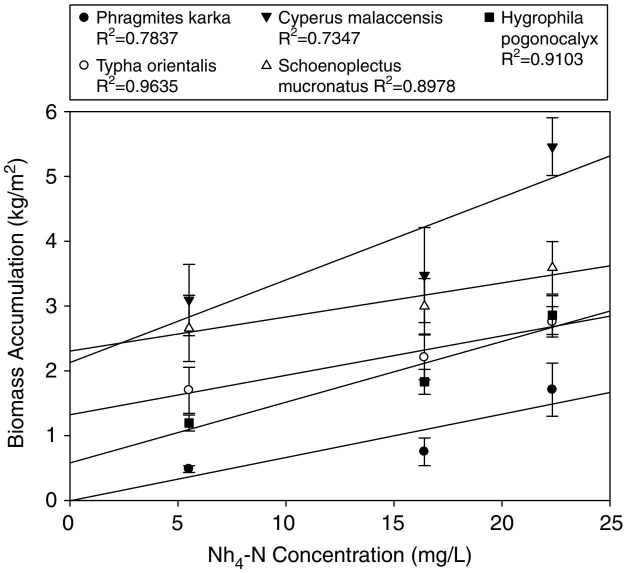

Fig. 7. The linear regression on the biomass accumulation versus NH_4-N.

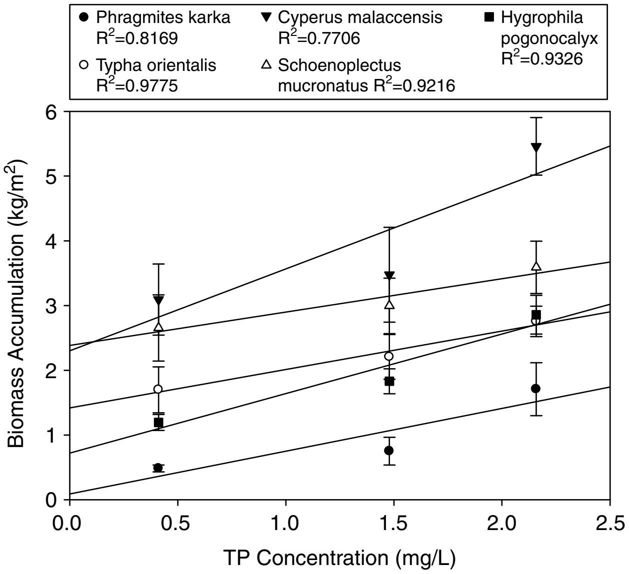

Fig. 8. The linear regression on the biomass accumulation versus TP.

In all macrophyte species, PK is an approximate species of the common reed (*Phragmites australis*, both of them are in same generic name: *Phragmites*), the latter is most commonly used in CWs. Earlier reports indicated that *Phragmites australis* needs 3–5 yr to achieve its maximum biomass which ranges from 413 to 9890 g m^{-2} [28]. In the present study, the highest final biomass of PK is 1708 g m^{-2} in the lower part of the range. This implies

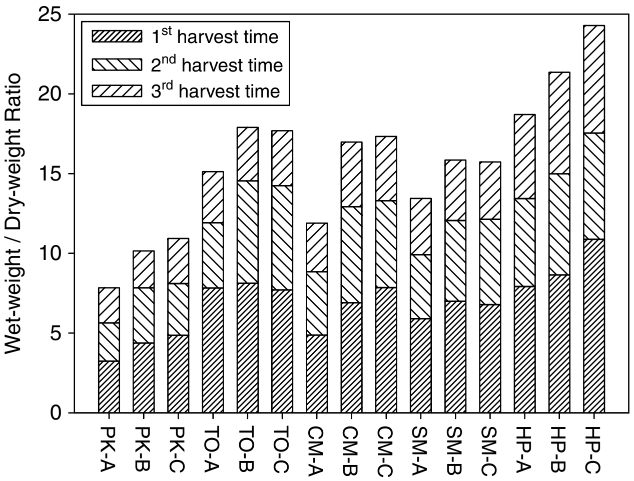

Fig. 9. The comparison on the drying ratio of all five macrophyte species the three sites.

that the maximum bioaccmulations of all five macrophyte species may possibly be higher than the observed values.

3.4. Drying ratio

Drying ratio is a non-dimensional indicator and defined here as the total (w/w) divided by the total dry-weight of a sample. The drying ratios of all groups are shown on Fig. 9. As shown, drying ratios significantly decreased from the first harvest to the third one. It means that the macrophytes decreased both the intake and content of water while they gradually matured. Unlike the other four monocotyledons, HP achieves full maturity before the second harvest time, since the value of drying ratio in last two harvest times at each site are very close.

Another notable observation is the increasing drying ratios of macrophytes from Site A to Site C. A plausible explanation is that the macrophytes which grow in lower concentration of nutrients need to ingest more water to obtain sufficient nutrients, therefore it results in an increased water content. In practical applications, drying ratio can be used as an indicator of the maturity of macrophytes for management of CWs.

4. Conclusions

High inlet concentrations of organic pollutants may cause lower removal rates and result in a inferior effluent water quality. However, if the total amount of pollutant removal is considered, the higher concentration of organic pollutants may lead to a larger amount of mass removal through a higher bioaccumulation in the tissue of wetland macrophytes and harvest.

Aside from the positive effect, high pollutant concentrations may also cause some negative ecological effect on the CW system. According to the experimental results, a stronger competition will occur due to higher growth rates under high nutrient concentrations. As from the in-situ observation in the study, the keen competition will eliminate some species which have lower growth rates through competition of space. Therefore, higher concentrations of pollutants will result in higher removal of total pollutant mass.

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