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Key controls and scale effects on sediment budgets: recent findings in agricultural upland Java, Indonesia

ALBERT I. J. M. VAN DIJK[1,2] &
L. A. SAMPURNO BRUIJNZEEL[2]

1 *CSIRO Land and Water, PO Box 1666, Canberra, ACT 2601, Australia*
albert.vandijk@csiro.au
2 *Vrije Universiteit Amsterdam, De Boelelaan 1085, NL-1081 HV Amsterdam, The Netherlands*

Abstract This study presents recent field research in a small agricultural catchment in upland West Java, and identifies the key controls, and scale effects, on sediment yields. Vegetative cover proved the dominant control on surface runoff and sediment generation, with additional variation attributed to slope and soil surface structure. Vegetation also provided the link between the water, sediment, and carbon cycles. Use of a process model to replicate and upscale field measurement to hillslope scale, highlighted the lack of a predictive theory linking vegetative cover to rainfall infiltration, as well as problems associated with the unaccounted covariance of terrain attributes that promoted sediment generation. At the hillslope to catchment scale, changes in slope gradient, and the presence of less erodible substrates became additional constraints on sediment yield. A conceptual framework to describe the changing importance of different sediment transport and deposition processes with increasing spatial scale was developed.

Key words carbon cycling; catchment sediment budget; ecohydrology; erosion processes; scale effects; sediment delivery

INTRODUCTION

Accelerated erosion continues to threaten agricultural production in the uplands of the Indonesian island of Java. Stream sediment also smothers freshwater and coastal-marine ecosystems, reduces the efficiency and lifetime of irrigation works and dams, and affects the navigability of lowland rivers. Numerous costly upland rehabilitation projects have resulted in widespread bench-terracing, but by-and-large have failed to decrease river sediment loads or enhance the well-being of upland farmers. This has given rise to a debate about the actual source(s) of river sediment and the time it takes for reductions in “on-site” erosion to result in decreased sediment fluxes downstream (Purwanto, 1999).

Between 1994 and 2001 the Vrije Universiteit Amsterdam and the Indonesian Ministry of Forestry carried out field research within the Cikumutuk Hydrology and Erosion Research Project (CHERP) to identify the socio-economic and biophysical causes for the small impact that past soil conservation programmes have had on catchment sediment yields in Java. Research included a variety of field experiments and measurements (Purwanto, 1999; Van Dijk, 2002). The results from these studies have helped identify key controls on sediment yield in this setting, and the way in which sediment yield varies with scale.

MATERIALS AND METHODS

Study area

All research was conducted in the 125 ha upper catchment of the Cikumutuk River near the town of Malangbong, about 40 km east of Bandung, West Java (7°03′S, 108°04′W, 580–610 m a.m.s.l.; Fig. 1(a)). Slopes are generally steep (mean ~15°). The substrate consists of volcanic breccias covered by 1–2 m of andesitic volcanic ash that has weathered to a kaolinitic oxisol dominated by silt and clay, and comprises several decimetres of highly permeable, well-aggregated soil over a much less permeable massive subsoil. The area experiences a humid tropical climate with a mean annual rainfall of ~2650 mm (1994–2001), of which more than two-thirds falls during the rainy season, from November to May.

Bench terraces are constructed on most hillsides for agriculture, and typically consist of a steep riser (0.5–1.3 m projected width), a compacted central drain (~0.3 m wide) along the contour, and a bed (0.8–5 m) that has a slight slope backwards to the central drain. Crops planted on the terrace beds usually included inter-cropped cassava and maize, sometimes with a third, lower crop.

Methods

A full description of all field research methods and results can be found in Van Dijk (2002; also available at www.geo.vu.nl/~trendy/CHERP.html). A catchment sediment

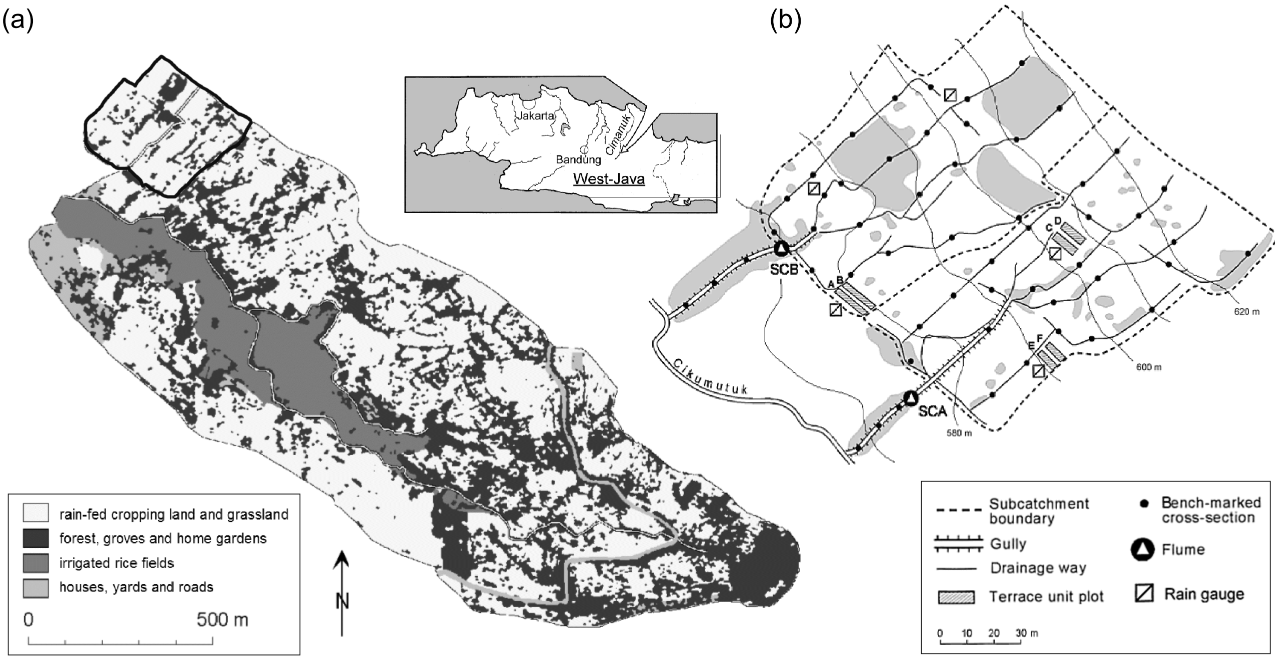

Fig. 1 Maps of: (a) land-use distribution in the study catchment (based on aerial photographs, September 1996); and (b) two hillside subcatchments from which surface runoff and sediment yield were measured (permanent vegetation is shaded).

budget was established by combining surveys of erosion and deposition in the drainage network with measurements of runoff and sediment generation for different forms of land use and management (settlement area, paddy rice fields, plantation forest, and rain-fed terraces with a variety of crops and soil conservation measures). The measurements were made across a wide range of scales, from 1- to 6-m^2 plots, via 50–230 m^2 terrace units, 0.1–0.3 ha fields and two 4 ha hillslopes, to the entire 125 ha catchment. Small-scale process research (Van Dijk *et al.*, 2003a,b) was used to develop a model of runoff and sediment generation on bench terrace units (TEST: Terrace Erosion and Sediment Transport), building on GUEST entrainment theory (Yu *et al.*, 1997). The model was used to evaluate different terrace management options (Van Dijk & Bruijnzeel, 2004a,b) and was applied to the hillside scale in an attempt to bridge terrace and hillside scales (Van Dijk *et al.*, 2004b). Water, sediment, carbon, and nutrient pools (in soil and biomass) and fluxes (in water, sediment and harvest) were measured for a typical rain-fed mixed cropping system, and for a young stand of fast-growing leguminous trees (albizia, *Paraserianthes falcataria*), and were used to establish the respective budgets.

RESULTS

Vegetation as the key control on sediment yield

By far the most sediment in the Cikumutuk River is derived from the cropped bench terraces (Table 1). Observations emphasized the 2-fold impact of vegetation in: (a) maintaining and increasing rainfall infiltration capacity; and (b) protecting the soil from rainfall impact. The effect of vegetation on rainfall infiltration is illustrated in Fig. 2(a). Higher than expected runoff can be attributed to soils with compacted surfaces, or to the presence of thin topsoil, and lower than expected runoff to deep topsoils or surface contact cover provided by low vegetation or mulching (Rose, 1993). Sediment concentration was also reduced by vegetative cover (Fig. 2(b)), but in addition, depended on surface contact cover, other modes of sediment transport (e.g. splash on small plots; see below), and tied ridges promoting deposition of coarser sediment. Sediment yield combined these two effects, and similarly showed a strong relationship with vegetative cover (Fig. 2(c)).

Table 1 Catchment sediment budget for 1995/1996 (after Van Dijk *et al.*, 2004b).

Land use	Area (ha)	Fraction of area (%)	SY (t $year^{-1}$)	SY (t ha^{-1} $year^{-1}$)	Fraction of catchment SY (%)
Rain-fed bench terraces	93	74	7500	81	82
Settlements, trails, roads	12	10	1000	83	11
Bank erosion and back-cutting	na	na	700	na	8
Dense vegetation	5	4	25	5	0.3
Paddy rice fields	15	12	–25	–2	−0.3
Cikumutuk catchment	*125*	*100*	*9200*	*73*	*100*

SY: sediment yield.
na: not applicable.

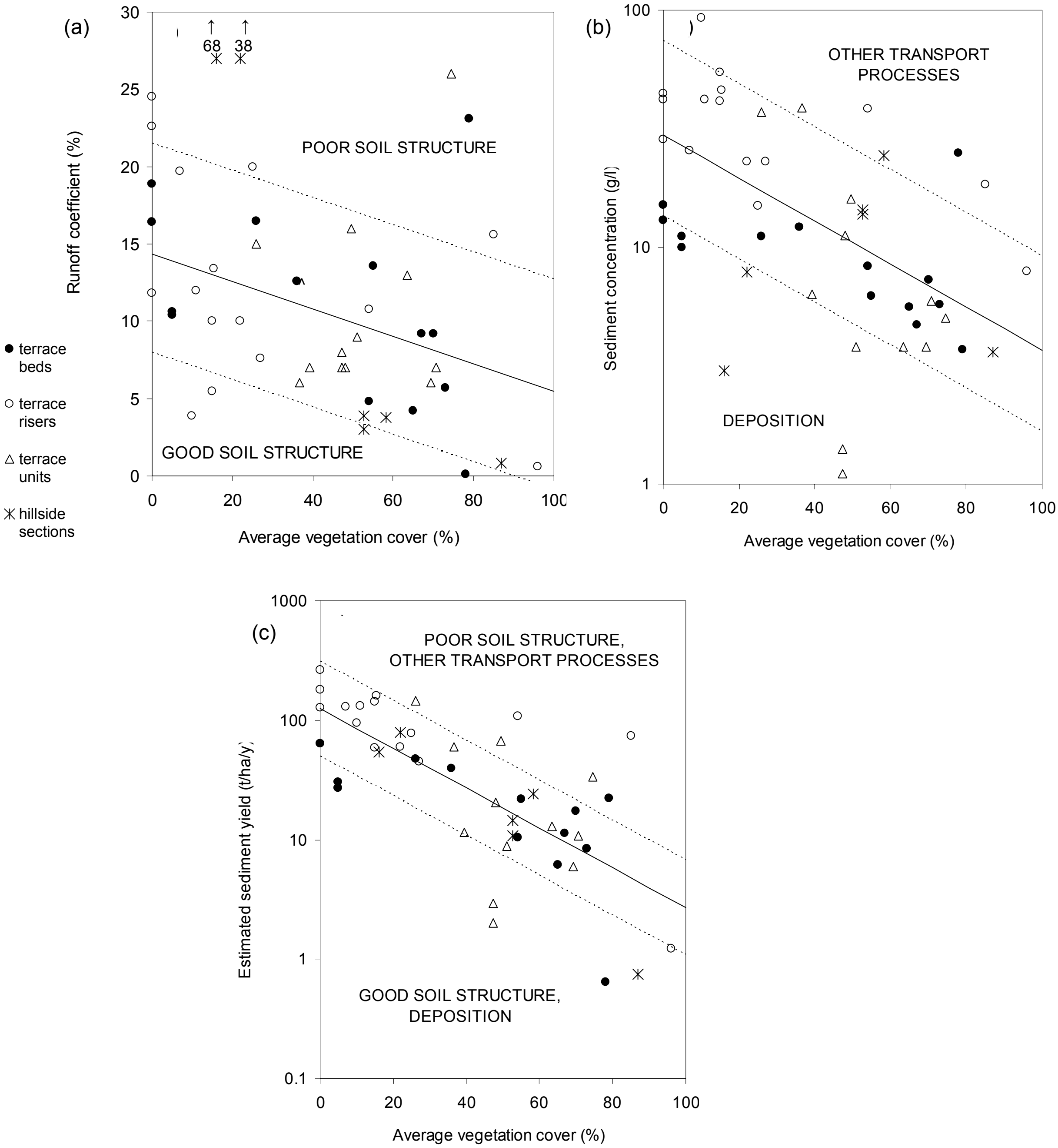

Fig. 2 Illustration of the relationship between vegetative cover (average for the measuring period) and (a) runoff coefficient (ratio of observed surface runoff and rainfall); (b) flow-weighted average sediment concentration; and (c) sediment yield (extrapolated to the average annual rainfall). Data are for plot sizes of ~1 m^2 to 4 ha under various land uses. The solid lines represent regression equations; the dashed lines exclude individual plots for which the deviation could be readily explained (see text) (note the logarithmic vertical scale in (b) and (c)).

Vegetation links water, sediment and carbon cycles

Research suggested a strong linkage between the water, sediment, and carbon cycles through vegetative cover. The sparse cover provided by the agricultural crops resulted in high surface runoff (~11% of rainfall), high soil loss (~40 t ha^{-1} $year^{-1}$), net loss of carbon (1.5-4.1 t C ha^{-1} $year^{-1}$, of which 0.9 t C ha^{-1} $year^{-1}$ was associated with sediment), and a decline in soil productivity. Conversely, the dense cover provided by the plantation forest was associated with very low surface runoff (0.8%) and sediment yield (0.7 t ha^{-1} $year^{-1}$), and strong carbon gains of 8.9 t C ha^{-1} $year^{-1}$ in biomass, and probably several tonnes more in the soil (Van Dijk *et al.*, 2004a). Situations have been reported in which greater vegetative cover does not result in a smaller surface runoff and sediment yield, typically because the canopy is high, the soil surface is disturbed, or litter has been removed (see above; Wiersum, 1984). However, these appear to be disturbance-related exceptions to the general rule that couples surface runoff, sediment yield and net carbon flux through vegetative cover.

Modelling sediment yields

The TEST model structure reflects the two stages in sediment transport observed on the bench terraces: (a) rainfall-driven transport by splash and shallow overland flow (wash) from the terrace riser and bed to the central drain; followed by (b) a combination of onwards wash transport of fine sediment, and runoff entrainment of coarser sediment from the central drain. The model was successfully validated, and predicted observed sediment yields well, but only when infiltration capacity was calibrated to reproduce observed runoff (Van Dijk & Bruijnzeel, 2004a,b). This highlights the lack of a reliable method to predict infiltration rates based on vegetative cover and soil surface conditions.

The TEST model also was used in a distributed fashion to simulate runoff and soil loss from two 4-ha terraced hillsides (Van Dijk *et al.,* 2004b; Fig. 1(b)). Upscaling was aided by the geometrically well-defined and relatively homogeneous bench terraces, but model performance was relatively poor and produced overestimates of runoff, and underestimates of runoff sediment concentration. It was concluded that the six erosion plots were not sufficient to provide a representative sample for model calibration. In addition, there was unaccounted covariance between important terrain attributes such as infiltration capacity, vegetative cover, slope, and soil conservation works; these tend to reinforce each other, and create erosion “hot spots”. Arguably, erosion plot methodology is ill-suited to deal with model upscaling because of the many replications required for a representative sample, and to establish all relationships between terrain attributes. Field surveys were of limited assistance because there was no method to provide quantitative estimates of infiltration characteristics for terrace units.

Sediment delivery and scale effects in sediment yield

The total amount of sediment in (temporary) storage in the hillslope drainage network was found to be small. When comparing sediment volumes generated on the bench terraces and that reaching the bottom end of two hillslopes, sediment delivery ratios (SDR) of 80–104% were obtained for two consecutive wet seasons. Given the large difference between bench terrace sediment yields (6-year average of 40 t ha^{-1} $year^{-1}$), and observed storage in the drainage network (<4 t ha^{-1}), SDR must be close to 100%

over longer time scales (Van Dijk *et al.*, 2004c). At smaller spatial scales, SDR was much more variable, and ranged from 13 to 191% for six different terrace units and periods of 106–130 days; the difference being stored in, or eroded from, the central terrace drain. Longer-term SDR values are hard to define at this spatial scale, as loose sediment in the terrace drain is usually moved back onto the terrace bed when farmers prepare the land during the dry season. These contrasts illustrate the effect of spatial and temporal scale(s) on SDR, and suggest that SDR variability decreases with increasing scale (cf. Walling, 1983).

The TEST model was used to simulate changes in sediment yield (in t ha^{-1} year^{-1}) with increasing spatial scale for a year with average rainfall. The model employed calibrated parameters, average values for terrain attributes, and representative observed slope form, and surface runoff concentration patterns (details available from the authors). Figure 3(a) shows the simulated change in sediment yield, and the relative importance of different processes at different scales moving from a decimeter scale on terrace risers and beds (the average sediment yield for the two is shown), via terrace units and the hillside, to the Cikumutuk catchment outlet ~10 km away (the steep stepwise changes are associated with the transition from terrace risers/beds to central drain, and from there to hillside trails and gullies, respectively). Measured sediment yields at larger scales were lower than those modelled (Fig. 3(a)) because, contrary to model assumptions, readily erodible material was not available in the hillside drainage network. Clearly, SDR strongly depends on two spatial scales being compared.

A hypothetical conceptual model of the scale-dependency of sediment yields is illustrated in Fig. 3b. This was constructed by assuming a hypothetical hillslope profile comparable to the one underlying Fig. 3a, but smoothed (15% slope at 0.1 m, via 5% at 21 m, to 1% at 300 m). Five domains can be distinguished, each with its own dominant sediment transport or deposition process, and each having a different relationship between sediment yield (SY) and slope length (L):

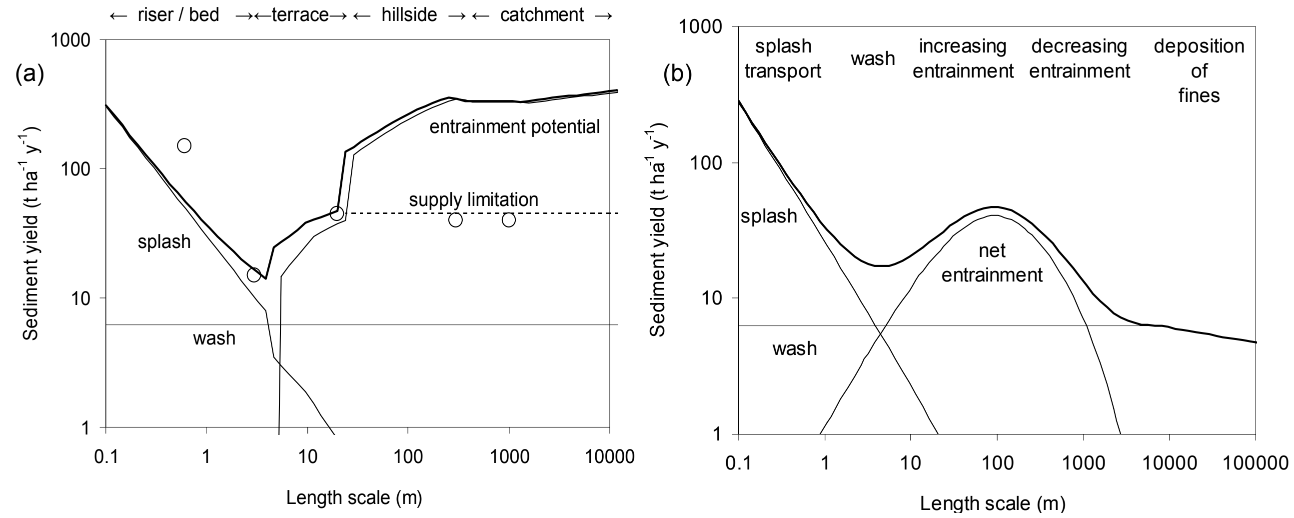

Fig. 3 Illustration of the relationship between length scale and sediment yield for (a) the studied terraced environment, compared with (b) an idealized non-terraced hillslope. The open circles in (a) represent typical sediment yields for (from left to right) a terrace riser, terrace bed, terrace unit, a hillside and the study catchment (based on data from Van Dijk & Bruijnzeel, 2004a,b; and Van Dijk *et al.*, 2004b).

(a) *Splash-transport dominated* (less than a few metres): sediment yield decreases inversely with length scale ($SY{\sim}L^{-1}$; Van Dijk & Bruijnzeel, 2004b);
(b) *Wash-transport dominated* (metres): fine rainfall-detached material is transported by surface runoff without any settling, and sediment yield approaches a situation in which it is independent of length scale ($SY{\sim}L^0$).
(c) *Increasing entrainment* (a few to 100s of metres): sediment yield increases as entrainment, by accumulating and concentrating surface runoff, increases. For straight slopes, the relationship with slope length typically is found to be $SY{\sim}L^{0.4–0.6}$ (Rose, 1993).
(d) *Decreasing entrainment* (10s of metres to kilometres): sediment concentrations stop increasing, or decrease as slope and/or sediment availability are reduced. The relationship with distance will depend on these two factors.
(e) *Deposition of fines* (more than kilometres): at sufficient distances, the flow rate will be reduced enough to allow fine material to settle out. Catchment sediment yield data suggest relationships of $SY{\sim}L^0$ to $SY{\sim}L^{-0.4}$. (Walling, 1983; Wasson, 2002).

The actual pattern and magnitude of change in sediment yield evolution will depend on many factors, of which probably the most important ones are rainfall, vegetation and soil cover, runoff generation, drainage density, slope gradient and form, substrate erodibility/sediment supply, the sediment particle size distribution, and the way these change over distance. Figure 3(b) provides a conceptual framework for interpreting the effect of scale on sediment yields and SDR.

CONCLUSIONS

Catchment sediment budgets can be established, with good confidence, by combining measurements of sediment storage and generation in the drainage network and from source areas of different sizes and land-uses. Bench terraces constructed for cropping proved to be the main source (>80%) of stream sediment in this environment.

Vegetative cover was shown to be the key control on surface runoff and sediment generation, with additional variation attributed to soil surface structure and cover, measurement scale, and slope. The water and sediment cycles were coupled to that of carbon through the control of vegetation. At hillslope to catchment scales, changes to lower slope gradients and less erodible substrates provided additional constraints on sediment yield in the studied environment.

Use of a process model to replicate and upscale field measurements to hillslope scale emphasized the need for a reliable predictive vegetation–rainfall infiltration theory, and methods for the rapid assessment of infiltration capacity in the field. Erosion plot technology appeared ill-suited to isolate all interrelationships between terrain attributes.

Some spatial and temporal scale issues were identified in applying the sediment delivery ratio concept. A conceptual framework was developed, describing five length-scale domains, each with its own dominant transport and deposition process.

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