Tropical-cyclone-driven erosion of the terrestrial biosphere from mountains

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The transfer of organic carbon from the terrestrial biosphere to the oceans via erosion and riverine transport constitutes an important component of the global carbon cycle[1–4]. More than one third of this organic carbon flux comes from sediment-laden rivers that drain the mountains in the western Pacific region[3,5]. This region is prone to tropical cyclones, but their role in sourcing and transferring vegetation and soil is not well constrained. Here we measure particulate organic carbon load and composition in the LiWu River, Taiwan, during cyclone-triggered floods. We correct for fossil particulate organic carbon using radiocarbon, and find that the concentration of particulate organic carbon fromvegetation and soils is positively correlatedwith water discharge. Floods have been shown to carry large amounts of clastic sediment[6].Non-fossil particulate organic carbon transported at the same time may be buried offshore under high rates of sediment accumulation[7–9]. We estimate that on decadal timescales, 77–92% of non-fossil particulate organic carbon eroded from the LiWu catchment is transported during large, cyclone-induced floods. We suggest that tropical cyclones, which affect many forested mountains within the Intertropical Convergence Zone[10], may provide optimum conditions for the delivery and burial of non-fossil particulate organic carbon in the ocean. This carbon transfer is moderated by the frequency, intensity and duration of tropical cyclones.

Mountain rivers carry a mix of clastic sediment and POC, mobilised by hillslope mass wasting at a rate proportional to the tectonic advection of rock mass in mountain belts[11,12]. The riverine POC is derived from vegetation, soil, and bedrock[13]. Erosion and burial of photosynthetically-derived organic carbon is a sink of atmospheric CO_2[4,14], reburial of fossil POC from sedimentary rocks[15] is not. It is therefore important to quantify the proportions of fossil and non-fossil POC in the river load, and the conditions of transfer which determine the likelihood of its burial. We have done this in a mountain river in Taiwan.

In Taiwan, as elsewhere in the west Pacific rim, intense precipitation, combined with high tectonic rates drive rapid mass wasting and fluvial sediment transfer[16]. These conditions promote rapid growth and erosional overturning of hillslope vegetation[17], and the delivery of soil and biomass to river channels. Erosion and sediment transfer peak during storm floods. Across the west Pacific there is a strong gradient in cyclonic storm activity, and Taiwan has a high tropical cyclone (typhoon) hit rate, about 3 per year[18]. There, we have focused on the LiWu River. Set entirely within a national park, it drains 435 km^2 of the densely forested (up to ~3000 m asl) Taiwan Central Range to the Pacific Ocean. Storage of sediment in its bedrock channel is limited and decadal sediment yields are known from river gauging[16].

To determine the quantity and source of POC in the LiWu River we have measured the organic carbon concentration (C_{org}) and ^{14}C of suspended load (Methods). ^{14}C helps define the proportion of non-fossil POC, since fossil POC from bedrock contains only a trace of ^{14}C. Suspended load samples were collected at water discharges (Q_w) of 1.1 to 12 times the 30 year mean (Q_{mean}=33 m^3 s^{-1}) (Figure 1 and Supplementary Table 1). In these samples C_{org} ranged from 0.16% to 0.42% and the fraction modern (from ^{14}C, Methods), F_{mod}, from 0.04 to 0.43 (Supplementary Table 1). Soils in the Taiwan mountains contain up to 10 times more organic carbon than suspended load samples with an average F_{mod}~1 (Supplementary Table 2). F_{mod} is likely ~1.1 in live vegetation (Methods). The low C_{org} and F_{mod} of riverine POC therefore reflect the dominance of clastic sediment supply by landslides, mobilising the rocky substrate and mixing non-fossil POC with large quantities of fossil POC from bedrock, as in other mountain belts around the Pacific[12,13].

We find that non-fossil POC concentration in the suspended load (POC_{mod}, the concentration of POC derived from vegetation and soil, in mg L^{-1}) was positively correlated with Q_w and there was no dilution at high Q_w (Figures 1 and 2). Such relationships are commonly invoked for clastic sediment transfer[19,20,21] where a power law relates suspended sediment concentration (SSC, mg L^{-1}) to Q_w, with variability in scaling reflecting the supply of clastic sediment. The non-linear increase in POC_{mod} with Q_w (Figure 2) implies a strong link between climate and the erosion of the terrestrial biosphere in this river catchment.

To assess whether this relationship may be a common feature of mountain rivers in forested topography, it is necessary to first consider the processes responsible for mobilising soil and vegetation from hillslopes. It is commonly thought that surface runoff (overland flow) delivers organic-rich particles from banks and soils to the river during moderate precipitation[22], and that rocky landslide debris dilutes non-fossil POC at high Q_w and SSC[13,23]. In a sample collected from the LiWu River at 1.1 times Q_{mean}, shortly after 22 mm of rain in 30 hours, F_{mod} = 0.41 (Supplementary Table 1), supporting this notion. However, samples taken at flood peaks during typhoons Mindulle (July 2004) and Aere (August 2004) had elevated POC concentrations, associated with an increase in F_{mod} and concentration of non-fossil POC (POC_{mod}, mg L^{-1}) in the suspended load (Figure 1). At the peak of the Mindulle flood 43% of suspended POC was derived from vegetation and soil. At that time intense precipitation (Figure 1) probably resulted in widespread transport of materials by overland flow[22], while landslides affected ~0.05% of the catchment area (Methods). Both mechanisms harvested photosynthetic organic carbon ranging from soil litter to tree trunks. Mechanical breakdown of this material during transport to typical suspended sediment grain size likely added to the observed increase in F_{mod} and POC_{mod} at the typhoon peak.

Samples collected after at least several hours of sustained rainfall show a positive non-linear relation between Q_w and POC_{mod} described by a power law (Figure 2). Samples collected during dry intervals also show a positive relationship but follow a power law with a lower exponent. Without rain, the principle source of non-fossil POC is river sediment in channels[12] containing mainly bedrock clasts. Moderate rainfall causes overland flow on hillslopes, washing soil and organic litter into the channel which increases POC_{mod}. During extreme rainfall, landsliding adds both photosynthetic and fossil carbon to this runoff flux. Overall, the effect of rainfall appears to be an increase in POC_{mod} for a given discharge by up to a factor five (Figure 2). Given the common nature of the erosion processes outlined here[12,13,22] this climatic control on POC_{mod} could be a general effect in humid mountain belts, influencing non-fossil POC yields.

Using the observed scaling of Q_w, POC concentration and POC_{mod}, we estimate that the total suspended POC in the Mindulle flood was ~14,200 tC, of which ~5500 tC came from non-fossil sources (Methods). The non-fossil flux represents a carbon yield of 13 tC km^{-2}, in a storm with a return time of 1/2 year. The total amount of organic carbon (soils and standing biomass) residing on Taiwan mountain slopes is ~$25x10^3$ tC km^{-2}[18,24]. Typhoon Mindulle therefore removed ~0.05% of the hillslope carbon store. This is similar to the proportion of the catchment disrupted by landslides (Methods) confirming that material delivered by mass wasting is an important source of suspended load non-fossil POC[12,13].

We assume that the two Q_w-POC_{mod} relationships in Figure 2 bound a likely range of POC_{mod} for a given Q_w, and combined them with the record of Q_w since 1970. This gives an average yield of non-fossil POC of 16 to 202 tC km^{-2} yr^{-1} for the LiWu catchment (Methods). Most of the uncertainty derives from the extrapolation to very high Q_w where no direct measurements of POC_{mod} are available. This estimate does not include coarse non-fossil POC which may float or travel in the bed load. Even so, this erosional flux of non-fossil POC is easily sustained by the present net primary productivity of the terrestrial biosphere[25].

The POC yield from the LiWu River is amongst the highest recorded globally[4,23]. Many small rivers in the Intertropical Convergence Zone (ITCZ) have high total POC yields[3,4], and 50 to 90 MtC yr^{-1} is thought to enter the oceans from islands of the west Pacific alone[5]. The corresponding average specific total POC yield is ~10-20 tC km^{-2} yr^{-1}, but this is not entirely comprised of recent atmospheric CO_2 and likely contains a fraction of fossil POC from bedrocks[15]. In mountain catchments outside the ITCZ where F_{mod} measurement allow quantification (US rivers: Siuslaw, Noyo, Navarro and Eel), non-fossil POC yields are ~5-8 tC km^{-2} yr^{-1}[13]. The LiWu and other upland rivers affected by large tropical storms, for example on North Island New Zealand[13], have non-fossil POC yields of 2-10 times greater.

Ultimately it is the burial of this atmospherically-derived POC in sediments that matters for long-term C cycling[4,14]. More than 90% of non-fossil POC is thought to be remineralised after entering the ocean[26]. However, floods from mountain catchments can have very high SSC[19] and large sediment loads (Figure 3), increasing offshore deposition rates and the burial efficiency of organic matter[7,8,9]. Importantly, many Taiwanese rivers deliver clastic sediment to the ocean at hyperpycnal SSC during typhoon floods[6,21]. Hyperpycnal river plumes can trigger turbidity currents that bypass shallow marine depocentres[19], transfer non-fossil POC direct to deep ocean basins and deposit thick sediment beds in which POC preservation is maximal. During the Mindulle flood, about 90% of the non-fossil POC was transported during 14 hours when the LiWu River had a hyperpycnal density (Methods). Extrapolating using measured POC_{mod} and Q_w (Figure 2), we estimate that since 1970, 77-92% of all non-fossil POC was transported in floods with a return time greater than 1/2 year and likely hyperpycnal SSC (Figure 3, Methods). In Taiwan such floods, during which the burial potential of non-fossil POC is maximal, occur almost exclusively during tropical cyclones.

Many mountain rivers are capable of reaching hyperpycnal concentrations. These turbid flows are influenced by a number of factors apart from large storms including earthquakes and bedrock lithology[20,21]. While lithology sets the sensitivity of a catchment to external triggers of erosion, earthquakes and associated hyperpycnal flows typically recur on timescales of centuries, even in orogens with very high rates of rock uplift and erosion[19]. In contrast, storms of varying magnitude occur on decadal or shorter timescales. The forested mountain belts of the ITCZ have an optimal combination of tectonic activity, driving rapid erosion, and frequent tropical cyclones[10] which cause floods that harvest modern organic carbon and clastic sediment and optimise the likelihood of burial. Outside the ITCZ non-fossil POC yields may be high, such as in New Zealand[12,13], but in the absence of frequent tropical cyclones only a limited fraction of this atmospheric CO_2 may be delivered by sediment-laden river plumes to the ocean. Tropical cyclones deliver heavy rainfall, driving the erosion of terrestrial biomass from slopes by common runoff and mass wasting processes[12,13,23]. This results in a positive relationship between POC_{mod} and Q_w in the river suspended load (Figure 2). Individual floods contribute to the erosion of non-fossil POC according to their return time, and in a catchment affected by tropical cyclones, the largest floods dominate in the long-term (Figure 3). These floods, occurring every ~1-10 years, have the highest density and greatest sediment loads, and are therefore also most likely to cause the geological burial of POC.

This mechanism explains the abundance of terrestrial POC in modern[27] and Cenozoic turbidites[28] within the ITCZ, and affects the total drawdown of atmospheric CO_2 through erosion of the terrestrial biosphere. Due to its dependence on floods (Figure 3), this carbon sequestration mechanism is sensitive to changes in the frequency of the most intense tropical cyclones. Such changes, which have been linked to the climate state of the ocean and atmosphere[10,29,30], have the potential to impact regional and global transfers of photosynthetic organic carbon from the terrestrial biosphere to the deep ocean. Increasing sea surface temperatures may increase the intensity of cyclones[30] and therefore enhance the transfer and storage of terrestrial biogenic POC in ocean sediments. Depending on the exact link to atmospheric CO_2, this may give rise to a negative carbon-cycle feedback on cyclone climate.

Methods Summary

Sampling and geochemistry of POC. Samples of suspended sediment were collected at Lushui station and filtered and dried on site. Water discharge and precipitation are measured automatically, at Lushui and within the catchment respectively. Soil samples were collected from uncultivated surface horizons across the Taiwan Central Range. After drying and homogenisation by grinding, sediments were leached with HCl to remove carbonate. Organic carbon concentrations were determined by elemental analyser-isotope ratio mass spectrometer (EA-IRMS) on a Costech-EA coupled via CONFLO-III to a MAT-253 IRMS[12]. An accelerator mass spectrometer (AMS) at NERC Radiocarbon laboratory, East Kilbride (Allocation numbers 1203.1006 and 1228.0407) was used to measure ^{14}C. Blanks of torched sand subjected to this procedure returned negligible concentrations of C. Organic ^{14}C standards subjected to carbonate removal returned F_{mod} within 1σ of consensus values.

Non-fossil POC and suspended sediment transfer. The co-variation of POC_{mod} and Q_w is described by a power law. Within the whole data set two different trends are recognised (Figure 2). Samples collected during rainfall episodes are closely fit by the power law $POC_{mod}=0.01*Q_w^{1.59}$ ($R^2=0.99$, $\chi^2=1.8$). All other samples have lower POC_{mod} at a given Q_w and are well described by a second power law ($POC_{mod}=0.02*Q_w^{1.11}$; $R^2=0.96$, $\chi^2=0.27$). These power laws were used as upper and lower bounds in predicting POC_{mod} for each day of the gauged record (1970-1999, 2003-2004). Suspended sediment rating curves based on our measurements and the full gauging record were used in a similar manner to investigate suspended sediment transfer.

Storm-triggered landslide mapping. Landslides were mapped by differencing LandsatTM satellite imagery acquired before and after typhoon Mindulle (18/06/2004, 20/07/2004) using ArcGIS software. Resolution is ~90mx90m. Mapped scars disrupt 0.23km^2 of the catchment.

References

1. Ittekkot, V. Global trends in the nature of organic-matter in river suspensions. *Nature* **332**, 436–438 (1988).

2. Meybeck, M. C, N, P, and S in rivers, From sources to global inputs. In *Interactions of C, N, P and S Biogeochemical Cycles and Global Change*, 163–193 (Berlin, Springer-Verlag, 1993).

3. Schlünz, B. & Schneider, R. R. Transport of terrestrial organic carbon to the oceans by rivers: re-estimating flux and burial rates. *Int. J. Earth Sci.* **88**, 599–606 (2000).

4. Stallard, R. F. Terrestrial sedimentation and the carbon cycle: Coupling weathering and erosion to carbon burial. *Glob. Biogeochem. Cycles* **12**, 231–257 (1998).

5. Lyons, W. B., Nezat, C. A., Carey, A. E. & Hicks, D. M. Organic carbon fluxes to the ocean from high-standing islands. *Geology* **30**, 443–446 (2002).

6. Milliman, J. D. & Kao, S. J. Hyperpycnal discharge of fluvial sediment to the ocean: Impact of Super-Typhoon Herb (1996) on Taiwanese rivers. *J. Geol.* **113**, 503–516 (2005).

7. Canfield, D. E. Factors influencing organic-carbon preservation in marine sediments. *Chem. Geol.* **114**, 315–329 (1994).

8. Burdige, D. J. Burial of terrestrial organic matter in marine sediments: A reassessment. *Glob. Biogeochem. Cycles* **19**, GB4011 (2005).
9. Galy, V. et al. Efficient organic carbon burial in the Bengal fan sustained by the Himalayan erosional system. *Nature* **450**, 407–410 (2007).
10. Webster, P. J., Holland, G. J., Curry, J. A. & Chang, H. R. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* **309**, 1844–1846 (2005).
11. Burbank, D. W. et al. Bedrock incision, rock uplift, and threshold hillslopes in the northwestern Himalaya. *Nature* **379**, 505–510 (1996).
12. Hilton, R. G., Galy, A. & Hovius, N. Riverine particulate organic carbon from an active mountain belt: The importance of landslides. *Glob. Biogeochem. Cycles* **22**, GB1017 (2008).
13. Leithold, E. L., Blair, N. E. & Perkey, D. W. Geomorphologic controls on the age of particulate organic carbon from small mountainous and upland rivers. *Glob. Biogeochem. Cycles* **20**, GB3022 (2006).
14. Hayes, J. M., Strauss, H. & Kaufman, A. J. The abundance of ^{13}C in marine organic matter and isotopic fractionation in the global biogeochemical cycle of carbon during the past 800 Ma. *Chem. Geol.* **161**, 103–125 (1999).
15. Blair, N. E. et al. The persistence of memory: The fate of ancient sedimentary organic carbon in a modern sedimentary system. *Geochim. Cosmochim. Acta* **67**, 63–73 (2003).
16. Dadson, S. J. et al. Links between erosion, runoff variability and seismicity in the Taiwan orogen. *Nature* **426**, 648–651 (2003).
17. Lin, K. C., Duh, C. T., Ma, F. C. & Wang, H. H. Biomass and nutrient content of woody debris in the Fu-shan subtropical broadleaf forest of northeastern Taiwan. *Taiwan J. For. Sci.* **18**, 235–244 (2003).
18. Wu, C. C. & Kuo, Y. H. Typhoons affecting Taiwan: Current understanding and future challenges. *Bull. Am. Meteorol. Soc.* **80**, 67–80 (1999).
19. Mulder, T. & Syvitski, J. P. M. Turbidity currents generated at river mouths during exceptional discharges to the world oceans. *J. Geol.* **103**, 285–299 (1995).

20. Hicks, D. M., Gomez, B. & Trustrum N. A. Event suspended sediment characteristics and the generation of hyperpycnal plumes at river mouths: East coast continental margin, North Island, New Zealand, *J. Geol*. **112**, 471– 485 (2004).

21. Dadson, S. et al. Hyperpycnal river flows from an active mountain belt. *J. Geophys. Res.* **110**, F04016 (2005).

22. Larsen, M. C., Torres-Sanchez, A. J. & Concepcion I. M. Slopewash, surface runoff and fine litter transport in forest and landslide scars in humid tropical steeplands, Luquillo experimental forest, Puerto Rico. *Earth Surf. Proc. Land.* **24**, 481–502 (1999).

23. Ludwig, W., Probst, J. L. & Kempe, S. Predicting the oceanic input of organic carbon by continental erosion. *Glob. Biogeochem. Cycles* **10**, 23–41 (1996).

24. Chang, Y. F., Lin, S. T. & Tsai, C. C. Estimation of soil organic carbon storage in a Cryptomeria plantation forest of northeastern Taiwan. Taiwan J. For. Sci. **21**, 383–393 (2006).

25. Zaks, D. P. M., Ramankutty, N., Barford, C. C. & Foley, J. A. From Miami to Madison: Investigating the relationship between climate and terrestrial net primary production. *Glob. Biogeochem. Cycles* **21**, GB3004 (2007).

26. Hedges, J. I., Keil, R. G. & Benner, R. What happens to terrestrial organic matter in the ocean? *Org. Geochem.* **27**, 195–212 (1997).

27. Nakajima, T. Hyperpycnites deposited 700 km away from river mouths in the central Japan Sea. *J. Sediment. Res.* **76**, 60–73 (2006).

28. Saller, A., Lin, R. & Dunham, J. Leaves in turbidite sands: The main source of oil and gas in the deep-water Kutei Basin, Indonesia. *AAPG Bull.* **90**, 1585–1608 (2006).

29. Emanuel, K. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* **436**, 686–688 (2005).

30. Elsner, J. B., Kossin, J. P. & Jagger, T. H. The increasing intensity of the strongest tropical cyclones. Nature 455, 92–95 (2008).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions R.G.H., A.G. and N.H. wrote the manuscript. M.C.C. collected the suspended load samples and R.G.H. and A.G collected soil samples. M.J.H. and H.C. provided hydrological data.

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Figure Captions

Figure 1: Source and concentration of riverine particulate organic carbon (POC) during typhoon floods in 2004. Frequent sampling of suspended load from the LiWu River, Taiwan in Julian Day time, with hourly water discharge (Q_w, m^3 s^{-1}) during typhoons Mindulle and Aere (light grey) and precipitation (ppt, in mm hr^{-1} multiplied by a constant factor 10) in dark grey. Note the difference in time increments between flood events. Grey diamonds show total particulate organic carbon concentration (POC_{tot}, mg L^{-1}). Non-fossil POC concentrations (POC_{mod}, mg L^{-1}, black circles) were calculated from F_{mod} (text) where stars indicate samples labeled in Figure 2. Both floods had high POC near peak discharge, caused by increased F_{mod} and POC_{mod}.

Figure 2: Positive, non-linear relationships between non-fossil POC concentration (POC_{mod}, mg L^{-1}) and water discharge (Q_w, m^3 s^{-1}). Dashed line is power law best fit through samples collected after sustained rainfall near the peak of typhoon-induced floods (shown with white stars, see also Figure 1) and outside the typhoon season (indicated by white triangle). R^2=0.99, χ^2=1.8. Dotted line is power law best fit through the remaining data (R^2=0.96, χ^2=0.3). For the available data these fits delimit a range of possible POC_{mod} for a given Q_w. The positive non-linear trend highlights an important role of climate to the POC_{mod} and it's transfer.

Figure 3: Cumulative discharge, suspended sediment and non-fossil POC transfer versus return time of a given flow. $RT_i=(T+1)/N_i$ where RT_i is return time (yr) of the ith observation, T the length of the record (32 years), and N_i is rank of ith observation, daily water discharge (Q_w), suspended sediment (SS) and non-fossil POC (POC_{nf}) transfer ranked in descending order with maximum at N=1. POC_{nf} transfer is calculated from Q_w with the models describing range of data (Figure 2). Dashed and dotted lines show mean Q_w and typhoon Mindulle flood (0.5 yr) RT, respectively. Floods dominate the erosion of POC from the terrestrial biosphere, with flows with RT>0.5 yr responsible for 77-92% of the total transfer.

Methods

Sampling. Suspended sediment samples were collected at the Lushui gauging station, LiWu River (24.1667°N, 121.5052°E), where water discharge (Q_w) is recorded by the Water Resources Agency (http://gweb.wra.gov.tw, Site 2460H005)[31] and precipitation by the Central Weather Bureau at La-Shao upstream of the gauging station (C1T800, 24.2064°N, 121.4458°E). For each sample 250 ml of turbid water were collected from the surface of the main channel where turbulence was evident, in a wide-mouthed plastic bottle thoroughly rinsed with river water. This assumes negligible difference in POC concentration in suspended load within the turbulent channel[32]. Samples were filtered through 0.2 μm nylon membrane filters checked for damage after filtration to avoid sample contamination. Each sample was dried at 80°C, weighed to determine suspended sediment concentration (SSC, mg L^{-1}) and stored in sealed glass dishes. Blanks (n=3) of torched sand was subjected to the same procedure. Approximately 500 cm^3 of bulk soil were sampled from surface horizons (A-E) from uncultivated areas across Taiwan Central Range (n=10).

Geochemistry. River load and blank were homogenised by grinding in an agate mill. Soils were homogenised using a mill grinder. The ground mass was acidified with 5M HCl and heated to 80°C for 4 hours to remove detrital carbonate[12]. A similar procedure was performed on two ^{14}C standards (IAEA-C5; TIRI-Barleymash) to quantify bias introduced by this carbonate removal on organic matter. Concentrations of organic carbon (C_{org}) were determined by combustion at 1020°C in a Costech elemental analyser coupled via a CONFLO III to a MAT 253 stable isotope ratio mass spectrometer. Analysis of the blank returned negligible concentrations of carbon (0.93μg), representing 1.7% of the typical amount of C in each sample aliquot. ^{14}C was measured by AMS after graphitisation of samples at NERC Radiocarbon laboratory, East Kilbride. ^{14}C standards subjected to the carbonate removal procedure returned ^{14}C within 1σ of consensus values. The fraction of modern ^{14}C (fraction modern, F_{mod}) is quoted in the text and can be >1 in living matter depending on the variable incorporation of excess ^{14}C from nuclear tests[33], through to 0 when a sample contains no ^{14}C. Surface bulk soil horizons (A-E) from the Central Range Taiwan have an C-weighted average F_{mod}=0.98±0.07 (n=10, ±1 standard deviation, Supplementary Table 2). We therefore assume that the non-fossil end member has F_{mod}=1 and fossil F_{mod}=0.

POC and suspended sediment transfer. During typhoon Mindulle POC_{mod} and Q_w displayed a correlation that can be described by a power law ($POC_{mod}=(3.23*10^{-9})*Q_w^{4.03}+1.66$, R^2=0.99, χ^2=0.6). With this power law model we obtained a non-fossil POC transfer of 5500 tC for the full hydrograph of the Mindulle flood from 01/07/2004 07:00 to 12/07/2004 23:00[31]. For the same period total POC concentration (POC_{tot}, mg L^{-1}) was related to Q_w ($POC_{TOT}=0.30*Q_w^{1.10}$, R^2=0.87) and SSC and Q_w were fit by a power law rating curve ($SSC=0.76*Q_w^{0.87}$, R^2=0.93) giving a total (fossil+non-fossil) POC transfer of 14,200 tC and a suspended sediment load of 3.88 Mt for the flood. Combining, the average $C_{org}*F_{mod}$ for the flood was 0.14%, a realistic value. With daily Q_w for 1970-1999, 2003-2004[31] long term non-fossil POC yields can be estimated, but samples collected during typhoon Mindulle in 2004 may not represent average conditions. Indeed, the Mindulle rating curve predicts unrealistic POC_{mod} of 820 g L^{-1} for the highest Q_w of 3760 m^3 s^{-1} in July 1982. POC_{mod} values in other samples do not lie on the Mindulle trend (Figure 2). Instead they are described by two power laws that describe upper and lower bound states related to the supply of non-fossil POC as described in the main text. Using these power laws ($POC_{mod}=0.01*Q_w^{1.59}$, R^2=0.99, χ^2=1.8; $POC_{mod}=0.02*Q_w^{1.11}$, R^2=0.96, χ^2=0.27) we predict a range of POC_{mod} for a given Q_w and investigate the long term behavior of the system in the context of the bounds predicted by these two models.

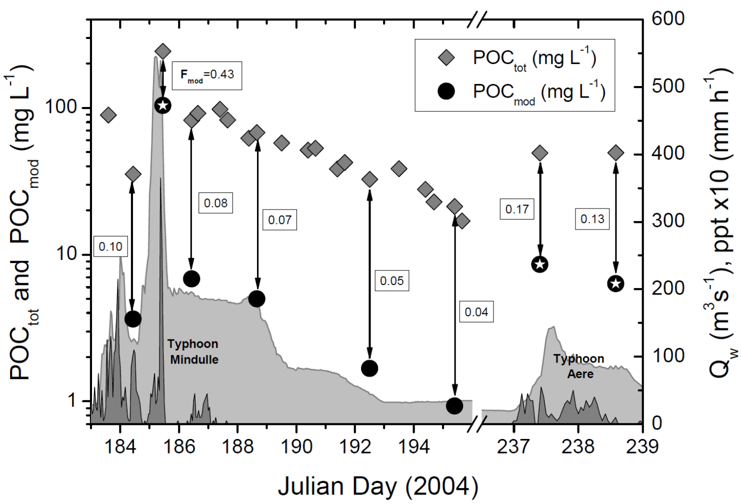
We have three different estimates of the suspended sediment transfer in the LiWu River. Monthly weighted averaging of Q_w and SSC data from 1970 (n=553) gives a sediment yield of 33,000 t km^{-2} yr^{-1}[15]. A rating curve based on our own measurements of SSC and Q_w in 2004 ($SSC=55.58*Q_w^{1.17}$, R^2=0.82, Supplementary Figure 1, Supplementary Table 1) gives 77,000 t km^{-2} yr^{-1} when applied to the Q_w record since 1970. According to this rating curve, ~80% of sediment is transferred by floods with a return time of >1/2 year (Figure 3). However, 2004 SSC data is at the upper end of values measured since 1970 (Supplementary Figure 1), and we consider this yield to be an upper bound. For comparison, a rating curve based on a least squares best fit of the full gauging record of

the Taiwan Water Resources Agency (SSC=314.37*$Q_w^{0.61}$, R^2=0.33, Supplementary Figure 1) gives a sediment yield of 13,000 t km^{-2} yr^{-1}, which we consider to be a lower bound on the sediment transfer in the LiWu River (Figure 3).

31. Data from the Water Resources Agency (WRA), Ministry of Economic Affairs, Taiwan, http://gweb.wra.gov.tw, Lushui Gauging Station 2460H005 (2008).

32. Gomez, B., Trustrum N. A., Hicks D. M., Rogers K. M., Page M. J., & Tate K. R. Production, storage, and output of particulate organic carbon: Waipaoa River basin, New Zealand. *Water Resour. Res.* **39**, 1161 (2003).

33. Levin, I. & Hesshaimer, V. Radiocarbon - A unique tracer of global carbon cycle dynamics. *Radiocarbon* **42**, 69-80 (2000).


POC_tot (mg L^-1)
POC_mod (mg L^-1)
F_mod=0.43
0.10
0.08
0.07
0.05
0.04
0.17
0.13
Typhoon Mindulle
Typhoon Aere
POC_tot and POC_mod (mg L^-1)
Q_w (m^3 s^-1), ppt x10 (mm h^-1)
1
10
100
0
100
200
300
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184
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Figure 1

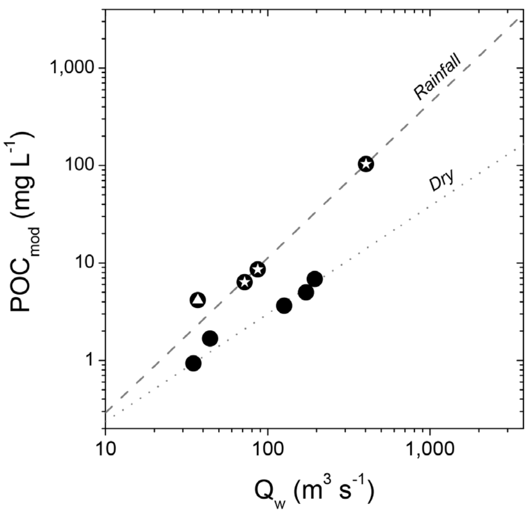

Figure 2

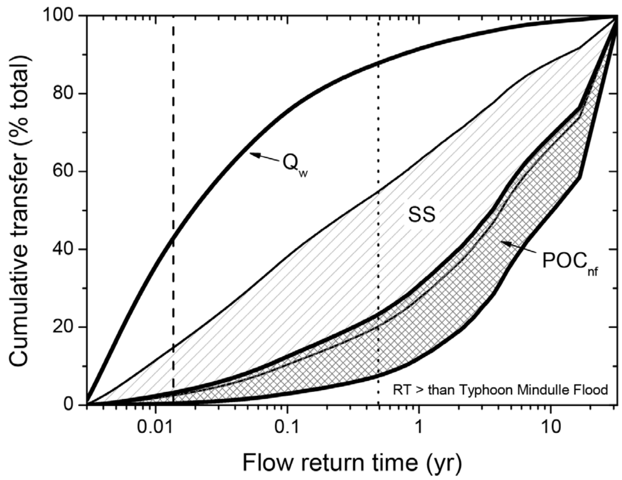
Cumulative transfer (% total)
Flow return time (yr)
100
80
60
40
20
0
0.01
0.1
1
10
Q$_w$
SS
POC$_{nf}$
RT > than Typhoon Mindulle Flood

Figure 3