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 from vegetation and soils is positively correlated with 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 particulate organic carbon (POC), mobilized 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 (refs 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 that determine the likelihood of its burial. We have done this for a mountain river in Taiwan.

In Taiwan, as elsewhere in the west Pacific rim, intense precipitation, combined with high tectonic rates, drives 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 ~3,000 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 (see the Methods section). ^{14}C helps define the proportion of non-fossil POC, because 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 ($Q_{mean} = 33\ m^3\ s^{-1}$) (Fig. 1 and Supplementary Information, Table S1). In these samples C_{org} ranged from 0.16% to 0.42% and the fraction modern (from ^{14}C, see the Methods section), F_{mod}, from 0.04 to 0.43 (see Supplementary Information, Table S1). Soils in the Taiwan mountains contain up to ten times more organic carbon than suspended load samples with an average $F_{mod} \sim 1$ (see Supplementary Information, Table S2). F_{mod} is probably ~1.1 in live vegetation (see the Methods section). The low C_{org} and F_{mod} of riverine POC therefore reflect the dominance of clastic sediment supply by landslides, mobilizing 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 (Figs 1 and 2). Such relationships are commonly invoked for clastic sediment transfer[19–21] 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 nonlinear increase in POC_{mod} with Q_w (Fig. 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 mobilizing 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

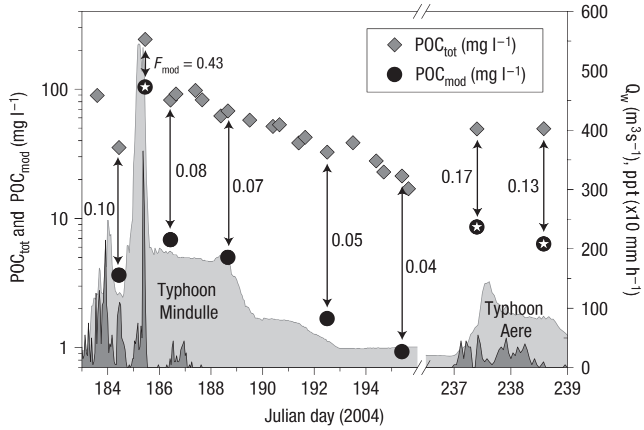

Figure 1 Source and concentration of riverine POC during typhoon floods in 2004. Frequent sampling of suspended load from the LiWu River, Taiwan, in Julian day time, with hourly water discharge (Q_w m^3 s^{-1}) during typhoons Mindulle and Aere (light grey) and precipitation (ppt, in mm h^{-1} multiplied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

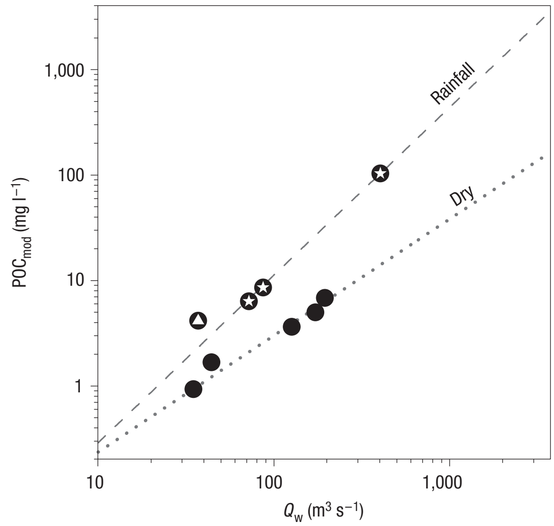

Figure 2 Positive, nonlinear relationships between non-fossil POC concentration (POC_{mod} mg l^{-1}) and water discharge (Q_w m^3 s^{-1}). The dashed line is the power-law best fit through samples collected after sustained rainfall near the peak of typhoon-induced floods (shown with white stars, see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

SSC (refs 13,23). In a sample collected from the LiWu River at 1.1 times Q_{mean}, shortly after 22 mm of rain in 30 h, $F_{mod} = 0.41$ (see Supplementary Information, Table S1), 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 (Fig. 1). At the peak of the Mindulle flood, 43% of suspended POC was derived from vegetation and soil. At that time, intense precipitation (Fig. 1) probably resulted in widespread transport of materials by overland flow[22], and landslides affected ~0.05% of the catchment area (see the Methods section). 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 probably 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 nonlinear relation between Q_w and POC_{mod} described by a power law (Fig. 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 seems to be an increase in POC_{mod} for a given discharge by up to a factor of five (Fig. 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 ~5,500 tC came from non-fossil sources (see the Methods section). 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 $\sim 25 \times 10^3$ tC km^{-2} (refs 17,24). Typhoon Mindulle therefore removed ~0.05% of the hillslope carbon store. This is similar to the proportion of the catchment disrupted by landslides (see the Methods section), confirming that material delivered by mass wasting is an important source of suspended-load non-fossil POC (refs 12,13).

We assume that the two Q_w–POC_{mod} relationships in Fig. 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 (see the Methods section). 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 local 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 50–90 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 composed of recent atmospheric CO_2 and probably contains a fraction of fossil POC from bedrocks[15]. In mountain catchments outside the ITCZ where F_{mod} measurement allows quantification (US rivers: Siuslaw, Noyo, Navarro and Eel), non-fossil POC yields are ~5–8 tC km^{-2} yr^{-1} (ref. 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 remineralized after

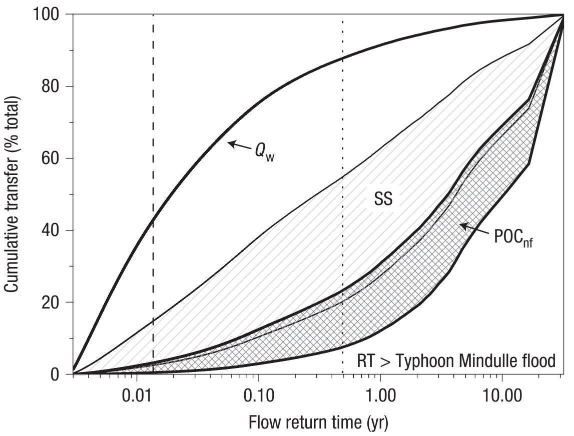

Figure 3 Cumulative discharge, suspended sediment and non-fossil POC transfer versus return time of a given flow. $RT_i = (T+1)/N_i$, where RT_i is the return time (yr) of the ith observation, T is the length of the record (32 years) and N_i is the rank of ith observation, daily water discharge (Q_w), 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 the range of data (Fig. 2). The 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.

entering the ocean[26]. However, floods from mountain catchments can have very high SSC[19] and large sediment loads (Fig. 3), increasing offshore deposition rates and the burial efficiency of organic matter[7–9]. 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 h when the LiWu River had a hyperpycnal density (see the Methods section). Extrapolating using measured POC_{mod} and Q_w (Fig. 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 probably hyperpycnal SSC (Fig. 3, Methods section). 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]. 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] that cause floods that harvest modern organic carbon and clastic sediment and optimize 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[12,13,22]. This results in a positive relationship between POC_{mod} and Q_w in the river suspended load (Fig. 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 (Fig. 3). These floods, occurring every ~1–10 yr, 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. Owing to its dependence on floods (Fig. 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 affect 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

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[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 was 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 SSC ($mg\,l^{-1}$) and stored in sealed glass dishes. Blanks ($n = 3$) of torched sand were subjected to the same procedure. Approximately 500 cm^3 of bulk soil was sampled from surface horizons from uncultivated areas across Taiwan Central Range ($n = 10$).

GEOCHEMISTRY

River load and blank samples were homogenized by grinding in an agate mill. Soils were homogenized using a mill grinder. The ground mass was acidified with 5 M HCl and heated to 80 °C for 4 h to remove detrital carbonate[12]. A similar procedure was carried out 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 1,020 °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 (0.93 μg), representing 1.7% of the typical amount of C in each sample aliquot. ^{14}C was measured by accelerator mass spectrometry after graphitization 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 from the Taiwan Central Range have a C-weighted average $F_{mod} = 0.98 \pm 0.07$ ($n = 10$, ±1 standard deviation, Supplementary Information, Table S2). We therefore assume that the non-fossil endmember has $F_{mod} = 1$ and fossil $F_{mod} = 0$.

POC AND SUSPENDED SEDIMENT TRANSFER

During typhoon Mindulle, POC_{mod} and Q_w exhibited a correlation that can be described by a power law ($POC_{mod} = (3.23 \times 10^{-9})Q_w^{4.03} + 1.66$, $R^2 = 0.99$, $\chi^2 = 0.6$). With this power-law model, we obtained a non-fossil POC transfer of 5,500 tC for the full hydrograph of the Mindulle flood from 07:00 on 01 July 2004 to 23:00 on 12 July 2004 (ref. 31). For the same period, total

POC concentration (POC_{tot} mg l^{-1}) was related to Q_w ($POC_{tot} = 0.30Q_w^{1.10}$, $R^2 = 0.87$) and SSC and Q_w were fitted by a power-law rating curve ($SSC = 0.76Q_w^{0.87}$, $R^2 = 0.93$) giving a total (fossil+non-fossil) POC transfer of 14,200 tC and a suspended sediment load of 3.88 Mt for the flood. Using these estimates, the average $C_{org}F_{mod}$ for the flood was 0.14%, a realistic value given our measurements (Supplementary Information, Table S1). With daily Q_w for 1970–1999, 2003–2004 (ref. 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 an unrealistic POC_{mod} of 820 g l^{-1} for the highest Q_w of 3,760 m^3 s^{-1} in July 1982. POC_{mod} values in other samples do not lie on the Mindulle trend (Fig. 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 ($POC_{mod} = 0.01Q_w^{1.59}$, $R^2 = 0.99$, $\chi^2 = 1.8$; $POC_{mod} = 0.02Q_w^{1.11}$, $R^2 = 0.96$, $\chi^2 = 0.27$), we predict a range of POC_{mod} for a given Q_w and investigate the long-term behaviour 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} (ref. 15). A rating curve based on our own measurements of SSC and Q_w in 2004 ($SSC = 55.58Q_w^{1.17}$, $R^2 = 0.82$, Supplementary Information, Fig. S1, Supplementary Information, Table S1) 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 (Fig. 3). However, 2004 SSC data are at the upper end of values measured since 1970 (see Supplementary Information, Fig. S1), 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 ($SSC = 314.37Q_w^{0.61}$, $R^2 = 0.33$, Supplementary Information, Fig. S1) 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 (Fig. 3).

Landslides were mapped by differencing LandsatTM satellite imagery acquired before and after typhoon Mindulle (18 June 2004, 20 July 2004) using ArcGIS software. Resolution is ∼90 m × 90 m. Mapped scars disrupt 0.23 km^2 of the catchment.

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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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