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Mobilization and transport of coarse woody debris to the oceans triggered by an extreme tropical storm

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Abstract

A significant consequence of Typhoon Morakot in August 2009 was the production of vast volumes of driftwood in Pacific Asia. We have quantified the flux of this coarse woody debris (CWD) to the oceans from typhoon-triggered landslides in Taiwan, where Morakot made landfall, by combining remote sensing (using FORMOSAT-2 imagery and aerial photography), analysis of forest biomass, and field observations. A total of 3.8–8.4 Tg CWD was transported to the oceans, carrying 1.8–4.0 Tg of organic carbon. In addition to the local effects on the marine and coastal environment from such a highly concentrated flux of carbon and nutrients, storm-driven mobilization of CWD may represent a significant, if infrequent, transfer of terrestrial biomass to the oceans. If the frequency of relatively rare, extreme storms such as Morakot increases in a changing climate, this transport mechanism may play an important role in feedbacks between global climate, storm intensity, and carbon cycling.

Dead trees and branches are now known to play key roles in forest ecology and hydrology (Gregory et al. 2003), including regulating biogeochemical cycling of carbon and other nutrients (Harmon et al. 1986), providing important species-specific habitats (Flebbe 1999), and creating structure in stream channels (Montgomery et al. 2003). Some woody material can also be exported from forests, but this process has not been quantified in such a way to make it possible to assess the effect both on downstream environments and on biogeochemical cycles from the regional to global scale. Though coarse woody material, defined as having diameter $>$ 10 cm, makes up a significant majority of the carbon pool in many forests (e.g., 36–88% in the forests studied by Naiman et al. 1987), organic material transport in rivers is typically thought to be dominated by dissolved organic carbon (DOC) and fine particulate organic matter (POM; typically $<$ 1mm) carried in the riverine suspended load (Meybeck 1982). In part this reflects the physical and chemical breakdown of coarse woody debris (CWD) on the forest floor and in stream channels (Johnson et al. 2006), but it also reflects a sampling bias. The total transfer of organic carbon in river systems is often assessed by chemical analysis of fine POM and DOC content in river sediments and waters, in parallel with hydrometric measurements (Mulholland 2003; Wheatcroft et al. 2010). This inevitably overlooks coarse material. A few studies have specifically considered the transport of coarse POM (1 mm–10 cm), typically by capturing stream-borne material in traps (Wallace et al. 1995; Johnson et al. 2006; Cordova et al. 2008). However most of this material is leaf, litter, and small wood fragments, and such studies have not captured the transport of the largest trunks and branches that make up CWD ($>$ 10 cm) because these are not typically mobilized under normal flow conditions.

Some work has explored the detailed mechanisms through which CWD is transported, using both observations of the distribution of varying wood fragment sizes in stream systems (Nakamura and Swanson 1994) and a combination of flume experiments with theoretical modeling (Braudrick and Grant 2000; Haga et al. 2002). These studies suggest that while small CWD can be removed by some stream and river systems, significant transport of large CWD is restricted by its large size relative to bank-full width of river channels, except where logs are input directly into high-order, wider rivers, such as by logging operations. However, large storms, by generating anomalously high bank-full discharge, should significantly enhance the capacity of stream networks for transporting CWD. In addition, precipitation during such storms may trigger mass wasting processes such as landslides on forested hillslopes (Hilton et al. 2008*a*), providing a significant new supply of biomass to stream channels. These combined effects raise concern over the impact of woody debris in exacerbating the damage caused by floods in populated areas (Haehnal and Daly 2004). Nonetheless, it has generally not been possible to directly observe mobilization and transport of CWD in major floods. While postflood distribution has been occasionally recorded (Pettit et al. 2005), there is no information about the total amount of wood that is mobilized by very large storms. In particular, the volume of woody debris that is exported

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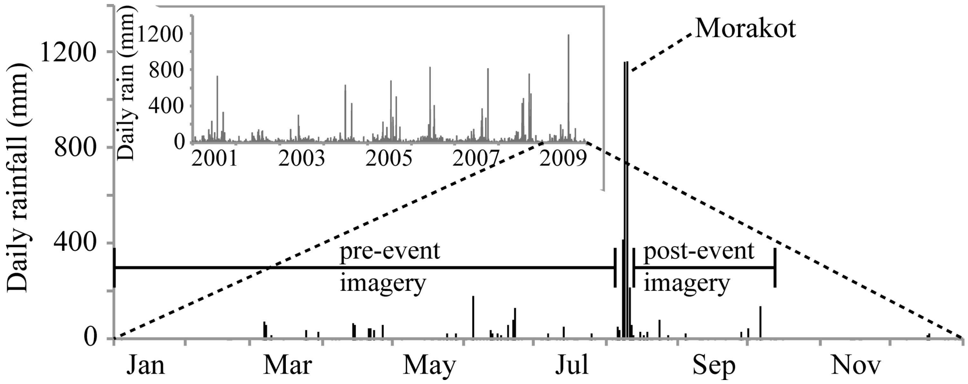

Fig. 1. Rainfall record for Alishan, Taiwan (Taiwan Central Weather Bureau, Climate Statistics: Daily Time Series; http://www.cwb.gov.tw/eng/index.htm), for 2009, showing heavy rainfall associated with Typhoon Morakot. Landslides triggered by the typhoon were assessed by comparing mosaics of FORMOSAT imagery collected before and after the event. Inset shows the 2009 precipitation in comparison with the record from the previous 10 yr.

from forests and transported to lakes and oceans by rivers is a complete unknown.

In addition to causing flood-associated damage, such transport could have important regional effects on lacustrine and coastal environments since woody material has distinct biogeochemical and physical roles in these aquatic settings (Maser and Sedell 1994; Wohl et al. 2009). It could also play an important role in the global carbon cycle if it delays the oxidation of organic material by sequestration in deep water or in sediment. The impact of tropical storms on forest vegetation has been shown to be significant, but it is not clear if the net effect is to release carbon to the atmosphere, through reduction of living biomass (Chambers et al. 2007; Zeng et al. 2009), or to trap carbon through burial of organic material in sediments, facilitated by transfer at high concentrations from the land surface to the oceans (Hilton et al. 2008*b*). Depending on their relative magnitudes and timescales, the balance between these effects may determine whether increased storm frequency and intensity acts as a negative or a positive feedback in response to changing climate. Woody debris that is carried by flooding rivers may be an important, unrecognized component of the storm–carbon system. This lends particular importance to quantifying storm-driven transport of CWD.

In this study we address this shortcoming by determining the total volume of woody debris that was mobilized by Typhoon Morakot and then quantifying the flood-driven fluvial export to the ocean. Morakot was a cyclonic storm that delivered near-record levels of precipitation to the island of Taiwan, with a maximum local rainfall of 2965 mm recorded over 4 d beginning on 07 August 2009 (Fig. 1; Taiwan Central Weather Bureau, Climate Statistics: Daily Time Series; http://www.cwb.gov.tw/eng/index.htm). Though rated only as a category 3 storm and with lower wind speeds than some other 2009 cyclones, Morakot formed in a monsoon trough and consequently delivered anomalous moisture (Ge et al. 2010). The resulting flooding caused significant loss of life and property damage (Ling et al. 2009), partly associated with riverbank collapse but largely because of widespread landsliding on steep mountain slopes. The coupling of this landsliding with high water flow in stream and river channels provided optimal conditions for mobilization and transport of CWD. We have combined analysis of remote sensing imagery, data on regional forest biomass, and field observations to determine the amount of CWD mobilized from hillslopes during the storm and subsequently transported to the oceans by rivers in Taiwan. This provides the first quantitative view of the significance of woody debris transport in large tropical storms, made possible by the availability of frequently acquired high-resolution imagery. Consistency of results from independent methods, with different fundamental assumptions, provides confidence in our approach.

Methods

We adopted two independent approaches to determining the volume of CWD transported by Morakot. The first method (biomass mapping) involved directly determining the total volume of woody material that was mobilized by landsliding in one large river catchment, the Kaoping (3320-km^2 area), based on remote sensing and land use mapping. The proportion trapped both in landslide deposits and in the river network was then assessed in order to determine by difference the volume of material transported to the oceans. The second method (reservoir accumulation) used the amount of wood recovered after the typhoon in the Tsengwen water reservoir (with catchment area of 505.8 km^2) to assess the total volume that was transported from the upstream area.

Results of the two methods, though independent, can be directly compared because both provide estimates of the volume of wood transported per unit of landslide area in each catchment (the CWD yield). Determining the total storm-driven CWD flux from Taiwan depends on extrapolating calculated yields to the scale of the entire island, based on the total area of event-triggered landsliding. Landslide areas were determined using high-spatial resolution satellite remote sensing imagery, following established approaches in Taiwan (Lin et al. 2004). FORMOSAT-2 satellite imagery, with a spatial resolution of 8 m in multispectral mode, was used to identify landslide areas across the entire island area (Fig. 2) based on a semiautomated routine. Images with minimal cloud cover were selected from before and after Typhoon Morakot as part of routine monitoring following storm events in Taiwan. Pre-event imagery for this study consisted of a mosaic collected between 01 December 2008 and 04 August 2009, and postevent imagery was collected between 21 August 2009 and 10 September 2009 (*see* Fig. 1). All images were orthorectified to a standard base image and checked manually using fixed visible markers to ensure spatial consistency over time. Bare areas are visibly distinguishable in FORMOSAT-2 images because of the high spatial resolution and the clear color contrast with vegetation. A semiautomated routine facilitated processing of each image. The Normalized Difference Vegetation Index (NDVI) was used to make a preliminary, supervised classification of bare areas; the exact NDVI threshold for bare areas differed from one image to another and was determined by tuning the cutoff value based on the visible contrasts. Clipped tiles (each 24 km^2, close to the FORMOSAT-2 swath size) were used in order to optimize this tuning by minimizing variability within each image. Classified areas were automatically clustered based on slope using a base-map digital elevation model to help identify bare areas not associated with landslides (e.g., roads and buildings). These were then manually checked and removed as appropriate. Finally, the classified landslide areas were checked individually and modified if necessary based on visual distinctions. Landslides resulting specifically from Typhoon Morakot were distinguished by overlaying the pre- and postevent imagery mosaics.

Biomass mapping method—Though FORMOSAT-2 imagery is well equipped to precisely map landslide areas because of its high spatial resolution, unfortunately it does not have the spectral range needed to be able to make direct inferences about forest biomass. Other remote sensing imagery with wider spectral range (e.g., LANDSAT) was found not to have the spatial resolution needed to determine total biomass at the scale of individual landslides. Instead, the total biomass harvested from landslide areas was determined for the Kaoping River basin by combining the FORMOSAT-2-derived map of landslide areas with land use maps derived from ground-verified aerial photography, along with information from permanent forest plot studies.

Within the Kaoping River basin, the areas affected by Morakot-triggered landslides were gridded at 8-m resolution and overlain on the Taiwan Forestry Bureau (TFB) digitized land use map (TFB 1995) in order to allocate land use and/or forest type to all areas disturbed by landslides. The TFB land use map is a 1:5000 map created from a comprehensive survey conducted from 1990 to 1993, defining land use across the island based on 74 categories. The survey used an islandwide mosaic of aerial photographs to generate a base map; a systematic grid system was used to select 286,925 points across the base map for detailed interpretation, and a subset of these, totaling 3996 points, or one every 3 km, was selected for validation and for ground sampling of forest, soil, and wildlife resources. At each ground sampling point, rectangular sample areas from 20 to 1000 m^2 were used to determine forest type, stand density, and diameter at breast height of trees in order to calculate timber density. The high resolution of the land use map means that it was well suited to attributing land use characteristics at the scale of landslides.

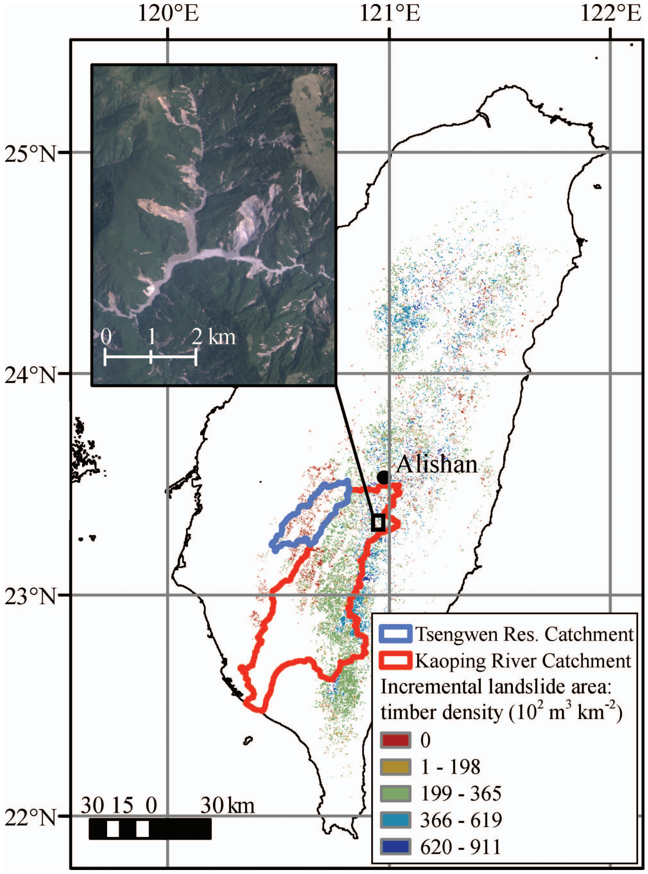

Fig. 2. Map of Taiwan, showing landslide areas identified as resulting from Typhoon Morakot, with color scale indicating the volume of timber accumulation based on the reported volumes for each forest type (Taiwan Forestry Bureau 1995). Inset shows FORMOSAT-2 imagery for identified region, illustrating the landsliding that stripped vegetation from hillslopes and supplied CWD directly to the river system. Black dot shows the location of Alishan, where the long-term precipitation record shown in Fig. 1 was collected.

Following allocation of land use and forest type across landslide areas triggered by Morakot, two approaches were used to calculate the total biomass that was removed (harvested) from hillslopes by the landsliding. The first method, the timber method, used the classification system of the TFB land use map together with TFB estimates of timber accumulation in each land use class (Fig. 2). The reported timber accumulation was determined as part of the 1993 survey by combining results from the ground sampling with data from monitoring of 2411 permanent forestry plots across 26 different forest types (TFB 1995). This method of calculating CWD production has dis-

Table 1. Biomass mobilized during landsliding in the Kaoping catchment.

Forest type	Landslide area (km^2)	Total forest biomass* (Gg km^{-2})	Mobilized total biomass (Tg)	Forest trunk + branch biomass (Gg km^{-2})	Mobilized trunk + branch biomass (Tg)
Conifer	17.3	26.5±5.4	0.4±0.1	17.9±5.0	0.31±0.09
Hardwood	73.2	38.7±8.9	2.8±0.6	24.0±8.0	1.76±0.58
Conifer–hardwood forest	15.0	32.6±10.4†	0.49±0.2	21.0±9.4	0.31±0.14
Bamboo forest	3.2	11.7±9.6	0.04±0.03	10.1±9.6	0.03±0.03
Mixed forest	10.2	22.2±14.2‡	0.2±0.1	15.5±13.5	0.16±0.14
Grassland and shrub	3.0	0§	0	0	0
Other (unvegetated)	7.9	0	0	0	0

* Total aboveground biomass plus soil litter and roots.

† Calculated as equal mixture of conifer and hardwood.

‡ Calculated as equal mixture of hardwood, conifer, and bamboo.

§ Total biomass assumed to be insignificant compared to the forest biomass.

advantages. It does not include contribution from bamboo forests to the CWD budget because this is not included in reported forest timber volume estimates (TFB 1995), and it does not allow calculation of the total biomass volume (i.e., including nonwoody biomass) involved in landsliding. In addition, total timber volumes may have changed between the 1993 survey and the time of Typhoon Morakot in 2009, though this effect is likely to be small compared to the uncertainty introduced by spatial heterogeneity of average forest age. The second method, the biomass method, involved separating land uses into seven general categories (Table 1) and classifying the typhoon-triggered landslides into these categories based on the more detailed 74 land use types described in the TFB (1995) inventory. For each category, average total biomass and average trunk + branch biomass were estimated from a compilation of studies on forest ecology in Taiwan (Lin and Ho 2005). This compilation includes data from 32 plot studies of biomass volume and distribution within forests; these were separated between hardwood (n = 8), conifer (n = 20), and bamboo (n = 4) in order to estimate average biomass totals for each forest type (*see* Table 1). Natural and plantation forests were not distinguished in this approach, in contrast to the method directly using TFB data. Biomass in conifer–hardwood mixed forest was assumed to be the equally weighted average of conifer and hardwood forest totals; mixed hardwood–conifer–bamboo forests were also assumed to have equally weighted average biomass. Attempts to independently infer total standing biomass across landslide areas from satellite imagery (Lefsky et al. 2002; Chambers et al. 2007) were undermined by the low spatial resolution (of LANDSAT imagery) and limited spatial and temporal coverage (of LIDAR imagery), though future developments in high-resolution satellite remote sensing (Houghton and Goetz 2008) promise to significantly improve this capability and reduce uncertainty of biomass estimates (presently as high as ± 50%; cf. Table 1) in future similar studies.

Not all the biomass destroyed by landsliding entered the river system. The position of landslides on hillslopes, which varies with triggering mechanism (Densmore and Hovius 2000), may mean that landslide material is physically separated from the river channel network. We used aerial photographs to assess the connectivity of post-Morakot landslides with debris flow and river channels by randomly selecting three 5 × 5-km plots from a grid of the Kaoping basin and manually separating landslides with and without visible links for biomass transport into the channel network. We calculated the proportion of landslide area within each plot where direct physical connection could allow for transport of material with the large size of CWD from landslides into the river network.

Even when landslides are connected to the river network, not all organic material was necessarily evacuated from the landslide areas. The total amount of CWD material on 11 landslide surfaces distributed across the basin was determined by measuring CWD line length in the orthorectified aerial photographs and by calculating trunk + branch biomass based on allometric scaling relationships. Woody biomass B_w can be described as a function of tree height h based on the equation

$$\ln(Bw) = a + b \cdot \ln(h) \tag{1}$$

where a and b are empirically derived coefficients specific to forest type. We used a = 6.14 and b = 4.6 based on coefficients from allometric studies of hardwood forest in Taiwan (Lin et al. 2006). Allometrically derived biomass was determined for each woody line segment measured in aerial photographs; these were summed to give the total CWD mass on landslide surfaces. Aerial photography does not capture burial of woody debris below the surface, and we used field observations of landslides to assess deep burial of CWD. We identified six deposits at a range of locations in the Kaoping basin where engineering work on roads and bridges left clean cross sections, and we assessed the belowground distribution of woody debris in each deposit. None of the observed landslides had any significant CWD buried below the surface, eliminating the need for detailed quantitative measurement.

Reservoir accumulation method—The second, independent method we used to determine the Morakot-triggered CWD yield was based on the accumulation of debris in Tsengwen reservoir. This was determined directly by the Taiwan Water Resources Agency, which is responsible for maintenance and operation of the reservoir, during operations to clean the reservoir following the typhoon (Council of Agriculture, Executive Yuan of Taiwan 2009).

This estimated volume is entirely independent of the remote sensing approach used in the biomass mapping.

Results

Mapped landslides resulting from Morakot covered an area of 404.3 km^2 across all of Taiwan. Within the Kaoping River basin, the area of typhoon-triggered landsliding was 129.8 km^2, equivalent to a landslide density of 3.9% on an area basis. An additional 38.0 km^2 of landsliding were identified within the Kaoping basin but were present prior to Typhoon Morakot. In the catchment upstream of Tsengwen reservoir, the typhoon-triggered landslide area totaled 14.2 km^2, or 2.8% of the total land surface area. The calculated landslide densities for the Kaoping and Tsengwen reflect concentrated landslide activity but are within the range reported in other settings for landslide erosion following major storms. A landslide density of up to ~ 5% was observed in Taiwan's Chenyoulan River basin, triggered by large typhoon storms in 2001 and 2004, following the 1999 ChiChi earthquake (Lin et al. 2008). A global assessment of regions affected by storm-triggered landslide activity between 1966 and 1976 found that 0.3–25% of areas surveyed were eroded by landsliding (Crozier et al. 1982). In this context, the observed density of Morakot-triggered landslides was high but not exceptional. However, one distinguishing feature of Marokot was the large total area of Taiwan that was affected, with landslides distributed across a majority of the mountainous area of the island (total land area of 35,980 km^2), much larger than either the area of the Chenyoulan catchment (367 km^2) or the largest landslide survey area in the global compilation reported by Crozier et al (1982) of 240 km^2.

Kaoping woody debris budget—Based on the timber method, using the distribution of landslides as a function of timber volume reported by the TFB (Fig. 2), the total yield of timber harvested from landsliding averaged $2.5 \pm 1.0 \times 10^4$ m^3 km^{-2}. For wood density of 613 ± 176 kg m^{-3} (Zanne et al. 2009), this means a yield of 0.015 ± 0.007 Tg km^{-2}, totaling 2.0 ± 0.9 Tg of timber over the entire mapped Kaoping landslide area.

Based on the biomass method, using land use coding of landslide areas and estimates of forest type biomass (Table 1), the harvesting of total biomass in the Kaoping basin, including aboveground biomass plus roots and soil litter, was 0.031 ± 0.005 Tg km^{-2}. This implies that the total biomass involved in landsliding amounted to 4.0 ± 0.7 Tg in the Kaoping basin and 12.5 ± 2.0 Tg across all the typhoon-triggered landslides in Taiwan. Based on the same approach, the specific mobilization of trunk + large branch biomass was 0.020 ± 0.005 Tg km^{-2}, totaling 2.6 ± 0.6 Tg of material for the Kaoping. This value for trunk + large branch material is within error of the estimate based on the timber method, using TFB timber volumes. The estimate from the biomass method is used in further calculations of the CWD budget for the Kaoping because it also includes contribution from bamboo forests, which are not included in the timber volume estimates.

Despite variability in the position of landslide failures and in the pattern of runoff, pervasive channelization means that, in all three of the 5 × 5-km plots that were studied, $< 1\%$ of landslide area was isolated from the channel system, meaning that this was not a limit on CWD transport. The very high degree of observed connectivity was most likely a consequence of the extremely high runoff generated by the typhoon, which would have decreased the area required to accumulate a flow depth capable of effectively transporting material.

Though virtually all landslides were connected to the river channels, trapped woody material was observed on some low-slope surfaces and behind local obstructions within deposits. The frequency distribution of CWD sizes remaining on landslide surfaces was positively skewed, with a log-mean total quantity of 154 mg km^{-2} and a 95% confidence interval (CI) of 41–585 mg km^{-2}. Over the area of mapped Kaoping landslides, this implies storage of 0.020 Tg (95% CI: 0.005–0.076) CWD on landslide surfaces. In terms of wood storage at depth, while all six deposits examined in the field had variable presence of woody debris on the surface, none had significant observable CWD buried below the top 1 m (where some of the debris at the surface was partially buried). Though fine-grained organic matter may be more uniformly distributed in landslides (Hilton et al. 2008*a*), our observations suggest that CWD is concentrated at the surface such that the observed surface occurrence reflects total storage in landslides.

Of the CWD that was removed from landslides, some remains trapped in the river network, with government surveys reporting 0.718 Tg of CWD in the Kaoping system (Council of Agriculture, Executive Yuan of Taiwan 2009). Of this, 0.545 Tg was removed during engineering work, preventing further quantitative evaluation in the field.

These results make it possible to calculate a total budget for CWD mobilization and transport in the Kaoping basin. Of the 2.6 ± 0.6 Tg CWD produced in Kaoping landsliding, 0.005–0.076 Tg remains stored on landslide deposits, and 0.72 Tg was retained in the floodplain. The remaining 1.2–2.5 Tg were transported to the oceans. Over the total landslide area in the Kaoping (129.8 km^2), this represents a specific yield to the oceans of 9.3–19.1 Gg km^{-2}.

Tsengwen reservoir woody debris budget—Results based on the quantity of wood recovered in Tsengwen reservoir after the storm can be compared with this value. A total of 473,000 m^3 of CWD were collected by the Taiwan Water Resources Agency immediately following Typhoon Morakot (Council of Agriculture, Executive Yuan of Taiwan 2009). Again using a wood density of 613 ± 176 kg m^{-3} (Zanne et al. 2009), this is equivalent to 0.290 ± 0.083 Tg CWD. This was sufficient to cover the reservoir surface in woody debris (Fig. 3). All the wood from the upstream catchment area was trapped by the reservoir, so this total reflects everything that was exported. In the absence of the reservoir, most of this CWD would have been transported to the oceans, though some would have been retained in the floodplains downstream of the reservoir. The budget for the Kaoping implies a wood retention ratio in river

Fig. 3. A water reservoir in Taiwan in the days following a major typhoon, showing the accumulation of coarse woody debris. Calculations of the total flux of this debris highlight the importance of such storms for transferring terrestrial biomass to the oceans and suggest that coarse material may play a significant role that is not accounted for in measurement of the amount of < 10-cm POC transported in river sediment (photo courtesy Po-Lin Chi).

channels of 0.2; in other words, 20% of CWD was retained along the river channels. Applying this ratio to the Tsengwen would mean that a total of 0.232 ± 0.066 Tg CWD would have been transported to the oceans from this catchment in the absence of the reservoir. Mapped landslides in the Tsengwen catchment make up 14.3 km^2, giving a specific CWD yield of 16.2 ± 4.6 Gg km^{-2}.

Discussion

The two independent estimates of CWD yield, one from reservoir accumulation and the other from landslide inventory, are consistent (*see* Table 2). If this range of yield applies to the landslide area across Taiwan, which is a reasonable assumption given the consistent results from the two distinct catchment areas, then a total of 3.8–8.4 Tg CWD were delivered to oceans and reservoirs as a result of Typhoon Morakot. Dammed river basins make up only a small portion of the total drainage area of Taiwanese catchments (3404 km^2, equivalent to 9% of the island surface area; Taiwan Water Resources Agency 2009), so most of this flux reached the oceans.

Most previous work has assessed the amount of organic material carried by rivers in terms of carbon flux. Based on average carbon content of 48.1 ± 0.8% for Taiwan woody biomass (Lin and Ho 2005), the Morakot-transported CWD carried 1.8–4.0 Tg C. Seo et al. (2008) quantified the riverine yield of woody debris from Japan by looking at records of CWD collected over multiyear periods (varying from 1 to 29 yr) from 131 reservoirs in Japan. Their results imply a total flux of 7.31 Gg C yr^{-1}, an annual flux nearly three orders of magnitude lower than the flux transported by the shorter-duration Morakot flood. In terms of area-normalized yield, the average value for Japanese reservoirs was 0.28 Mg C km^{-2} yr^{-1}, with individual reservoir catchments ranging in average yield from 0.02 Mg C km^{-2} yr^{-1} to 3.08 Mg C km^{-2} yr^{-1}. The Morakot-delivered yield from mountainous Taiwan (area 35,980 km^2), in contrast, represents 50–111 Mg C km^{-2}. Compared to the average background value observed in the Japan data set, the Morakot-triggered flux of CWD reflects ~ 200–400 yr worth of transport.

The importance of transport during storms like Morakot clearly depends on how frequently such events occur, which is poorly constrained. Rainfall recurrence interval statistics for Taiwan deviate from power law behaviour, particularly for large storms (Fig. 4; Taiwan Central Weather Bureau, Climate Statistics: Daily Time Series; http://www.cwb.gov.tw/eng/index.htm), possibly because storms such as Morakot appear to depend on the interaction between multiple meteorological systems (Ge et al. 2010). This makes it difficult to quantify return times for rainfall events of this magnitude. Analysis of the spatial distribution of biomass using remote sensing imagery, together with information on rates of forest regrowth on landslides, might provide some estimates of landslide frequency across the landscape, but this is not possible with current data. However, the landslide density associated with Morakot was not exceptionally high when compared with other large typhoon storms, suggesting that while this was an extreme event, it was not entirely anomalous. Even for a return time of > 50 yr, comparison with the observations from Japan suggests that an event such as Morakot represents a significant contribution to the long-term fluvial transport of CWD.

Moreover, our results indicate that, during such large storms, CWD may make up an important, broadly unrecognized part of the total budget of riverine carbon transport. Unfortunately it is not possible to directly estimate the total amount of particulate organic carbon (POC; i.e., the non-CWD, < 10-cm portion of organic material) or the total amount of DOC transported by Morakot itself. However, Hilton et al. (2008*b*) determined the flux of recent, biogenic POC transported by the Liwu

Table 2. Summary of calculated woody debris fluxes and yields.

Data source	Kaoping catchment		Tsengwen Reservoir catchment
	Timber volume method	Biomass method	
Mobilization of woody debris from landslides	2.0±0.9 Tg	2.6±0.6 Tg	0.29±0.08 Tg
Yield of woody debris into river system*	7.9–22.3 Gg km^{-2}	14.8–24.6 Gg km^{-2}	20±5.7 Gg km^{-2}
Yield of woody debris to the oceans*	6.3–17.8 Gg km^{-2}	9.3–19.1 Gg km^{-2}	16.2±4.6 Gg km^{-2}†

* Yield calculated relative to typhoon-triggered landslide area in each catchment.
† Reflects total that would have been transported in the absence of the reservoir.

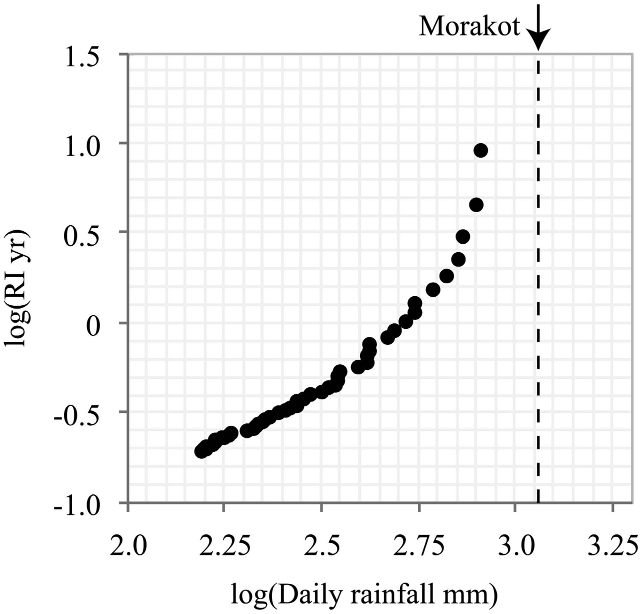

Fig. 4. Rank-recurrence interval (RI) of daily precipitation statistics at Alishan plotted against daily rainfall totals for data from 1999 to 2009. Lower-rainfall events show a Zipfian power-law distribution, but larger storms deviate from this relationship, suggesting that their underlying physical mechanism may also differ. This confounds attempts to extrapolate from the rainfall statistics in order to estimate the return time of an extreme event such as Morakot.

River in eastern Taiwan during Typhoon Mindulle in 2004, combining radiocarbon analysis of river suspended sediments and hydrometric measurements. Their calculated POC yield of 13 Mg C km^{-2} is a fraction of the CWD yield estimated from Morakot. The precipitation intensity was lower in Mindulle compared to Morakot, confounding direct comparison, but the contrast suggests that CWD is likely to play an important part in storm-event organic transport, at least for the very large storms that trigger extensive landsliding. This contrasts with nonstorm transport when, based on the analysis of Seo et al. (2009), a maximum of $< 10\%$ of total organic carbon transport occurs as CWD. We attribute this to the fact that high depths of river flow in extreme storms allow transport of woody material that would not be removed in smaller storms.

The Morakot-delivered CWD flux is distinguished not only by the significant role of coarse debris but also simply by its overall magnitude when compared with global fluxes of POC. The total Morakot-delivered CWD carbon flux represents 10–26% of the yearly flux of particulate carbon from the Amazon River, the largest point source of terrestrial carbon to the oceans (Schlunz and Schneider 2000). The Morakot yield of CWD (50–111 Mg C km^{-2}; *see* the previous discussion) is over an order of magnitude higher than the 2.6 Mg C km^{-2} transported over the entire year from the Amazon. A key characteristic of the Morakot flux was that it was delivered from a small area over a short amount of time, suggesting that, though major storms such as Morakot are rare, they may have a highly concentrated effect on the reservoir, coastal, and open-ocean environments where terrestrial organic material is delivered.

One of the key impacts of such highly concentrated CWD delivery is physical, with large areas of open water covered by debris. Driftwood generated by Morakot covered reservoirs (e.g., Fig. 3) and blocked harbors throughout Pacific Asia in the weeks following the event. This generated a range of secondary natural hazards (including for shipping and drinking-water supply). It also would have been accompanied by significant change in the physical conditions (light, temperature) of the shallow-water environment, yet the effect of such sudden, short-term disturbance on the marine environment is largely unknown.

The concentrated flux of woody debris associated with storms may play a key role in coastal and ocean ecology. Woody debris is known to be critically important to coastal, pelagic, and benthic ecological communities (Mortenson 1938; Gooding and Magnuson 1967; Hoyoux et al. 2009). Though it is known that the supply of woody material can have important effects on both surface and benthic ecosystems, it is not clear what the role of highly concentrated flux, such as that from a major storm like Morakot, may be. For example, episodic transport during large storms may be important for facilitating waterlogging and sinking of woody material.

If significant volumes of woody debris carried by flooding rivers do sink to the deep ocean, the net transfer of carbon may determine how storms influence the global carbon cycle. In the case of Morakot, the amount of CWD transported to the oceans makes up a significant portion (30–60%) of the total living carbon that was mobilized by landsliding. It is likely that a significant amount of noncoarse organic material was also transported to the oceans during the typhoon event itself. The remaining biomass is most likely to either decompose on land or be transported as sediment-borne POC during future storms after it is physically broken down on the forest floor or in stream channels. While around 80% of terrestrially derived organic carbon is thought to be decomposed in the oceans (Hedges et al. 1997; Burdige 2005), the transport, burial, and preservation of CWD in the oceans may differ significantly from POC, with slower oxidation rates and longer transport distances expected for the smaller surface-to-volume ratio of coarse material (Spanhoff and Meyer 2004). If significant amounts of carbon are preserved as a result of episodic, storm-driven flooding (Heezen et al. 1964), such as that associated with Morakot, then regrowth of forest vegetation on landslide surfaces and deposits (Restrepo et al. 2009) would lead to a net sink of atmospheric CO_2 over time scales of forest regeneration (Hilton et al. 2008*b*). This facet of storm-driven disturbance has not been accounted for to date (Chambers et al. 2007), and these effects may be particularly important if the frequency of such large storms, even if generally low, changes with global climate (Intergovernmental Panel on Climate Change 2007).

The observation that storms are capable of delivering quantitatively significant volumes of coarse organic matter to the oceans leaves open many questions about the fate of this material and its importance in the marine environment. The prevalence of steep, forested islands in the humid tropics means that transport of CWD driven by very large tropical storms may be an important pathway for transport of organic matter to the oceans that has not been previously recognized and deserves further attention.

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