

GEOLOGY

Damming the wood falls

Ellen Wohl* and Emily P. Iskin

Rivers historically transported unquantified volumes of driftwood to the ocean. Driftwood alters coastal sediment dynamics and provides food and habitat for diverse organisms. Floating driftwood supports open-ocean organisms. Sunken wood sustains seafloor communities. Centuries of deforestation, flow regulation, and channel engineering have substantially reduced riverine large wood fluxes to the oceans. Here, we use contemporary records of wood flux to reservoirs and coastal regions to estimate the magnitude of potential contemporary global wood fluxes. We estimate that 4.7 million m³ of large wood could enter the oceans each year (the 95% prediction interval range is ~300,000 to 70 million m³). This represents an upper bound for contemporary wood fluxes to the oceans because of wood removal from rivers and reservoirs and a lower bound for historical wood fluxes because of deforestation and river engineering. Substantial reduction of this wood flux likely negatively affects coastal and marine environments.

INTRODUCTION

Living trees are widely appreciated for the numerous ecosystem services that they provide in the context of carbon sequestration (1), modification of the climate and hydrologic cycle (2), erosion control (3), habitat and biodiversity (4), and timber resources (5). Dead trees, known as large wood in rivers or driftwood in oceans, have come to be more appreciated since pioneering research in old-growth forests revealed the role of standing and downed dead wood in providing nutrients and habitats to a wide array of organisms (6). Large wood that enters rivers and lakes plays an equally vital role in freshwater ecosystems. Large wood in rivers affects the distribution of hydraulic forces and facilitates instream storage of sediment and particulate organic matter (7, 8), enhances surface-subsurface connectivity and thus influences water chemistry (9), alters channel and floodplain morphology (10), and creates habitat diversity (7, 11). In lakes, dead wood provides food resources and habitat for diverse organisms (12, 13).

Rivers also create a conduit for delivering wood to coastal and marine environments, where the wood continues to influence ecosystems. Driftwood logs on sandy and gravel beaches trap sediment, plant litter, and propagules (14, 15). These accumulations can initiate formation of dunes and provide critical habitat for microbial communities, plants, invertebrates, and small vertebrates. Beaches with driftwood exhibit higher biodiversity than those from which wood is removed (16–18). Smaller fragments of wood increase retention of soil moisture in the coastal environment, provide organic substrate for seedling germination, and, when submerged in the near-shore zone, provide nutrients to invertebrates and fishes (19).

In the open ocean, driftwood provides vital habitat for microbial communities and invertebrates (20, 21). Open-ocean fish congregate around drifting wood for feeding, cover and refuge from predators, and removal of external parasites (22, 23). Driftwood ferries freshwater invertebrates into marine environments and moves species across ocean basins, as well as from the surface to the abyssal plains (24, 25). Some of the same microflora inhabit sunken wood and hydrothermal vents and some of the macrofauna are closely related, suggesting that sunken wood has served as stepping stones for the

evolutionary adaptation of organisms at deep-sea vents (26). Pieces of large wood that sink to the seafloor are known as wood falls [e.g., (27)]. Wood falls create an oasis of habitat and food in the barren abyss of the ocean bottom, and distinctive communities of fungi, mollusks, and crustaceans thrive in the submerged wood (27, 28).

Driftwood and wood falls to the seafloor depend on wood production and transport by rivers to the ocean. Production reflects the primary productivity and spatial extent of forests. Transport reflects recruitment of dead wood to river corridors, movement downstream to coastal areas, and movement along coastlines and across ocean basins. Human activities during the past few centuries have reduced wood supply to the oceans by altering every component of production, recruitment, and transport. These alterations have accelerated during the past century.

At least some portion of Earth has been forested since 385 million years ago, when river wetlands supported tree ferns and other woody plants with trunks 30 m tall (29). Before industrialization, forests covered approximately 40% of Earth's landmass, but global forest cover has now shrunk to an estimated 28% (30) and deforestation continues rapidly in some parts of the world. Opportunities to produce dead wood have thus declined significantly.

Recruitment of wood to river corridors occurs via individual and mass tree mortality that introduces downed wood to a river channel. Tree mortality can result from normal aging and death or from processes including bank erosion that undercuts riparian trees, hillslope mass movements that reach river corridors, wildfire, blow-down of trees during hurricanes or other strong winds, and insect infestation (31). Reduced forest cover, especially in proximity to river channels, has reduced recruitment, but perhaps the greater effect is the removal of wood that does enter rivers. Large wood has been intensively removed from channels to facilitate navigation, control floods, and reduce hazards to infrastructure for at least two centuries, and the limited systematic records kept in regions such as the continental United States indicate that millions of logs were removed from rivers during the 19th and 20th centuries (6, 32). As large dams were built on many rivers during the 20th century, wood was also removed from the reservoirs created by these dams (33). Removal of wood from channels and reservoirs thus significantly reduced wood transport to the oceans.

Driftwood removal from beaches is undertaken largely for aesthetic reasons and is widespread along the coastlines of industrialized

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Department of Geosciences, Colorado State University, Fort Collins, CO 80523-1482, USA.

*Corresponding author. Email: ellen.wohl@colostate.edu

countries (17). Driftwood that clogs harbors or affects shipping is also removed (34). Removal of driftwood from coastal and nearshore environments represents another reduction in wood transport.

Loss of forest cover has received a tremendous amount of attention because of the effects on terrestrial ecosystems, but loss of wood inputs to the oceans is less recognized. This derives partly from the almost complete absence of relevant data. The amount of wood entering the oceans before industrialization remains unknown, as does the amount of wood entering the oceans under current conditions. The proportions of wood entering the oceans that is retained on beaches, remains floating in the open ocean, or sinks to the seafloor are similarly unknown. Here, we review existing data on riverine wood exports to artificial reservoirs and the ocean and develop a first-order approximation of potential contemporary wood export to the ocean. Our intent is to enhance recognition of the importance of riverine wood fluxes to the ocean and spur efforts to quantify and restore these fluxes.

RESULTS

We collected published data on average annual wood export to reservoirs and estimated wood export to the ocean during extreme storms (table S1). This calibration dataset includes 197 values for annual wood export and wood export during extreme storms across contributing drainage areas ranging from 6 to 797,385 km². Rivers in the calibration dataset span the biome range of the tropics to the boreal regions of Siberia. We first applied a logarithmic transformation to the data (both the drainage areas and wood export values) to better meet the assumption of normality and then performed linear regression (Fig. 1). The equation for the best-fit regression line (adjusted $R^2 = 0.49$, $P < 0.001$) is (with large wood export in cubic meters per year and drainage area in square kilometers)

$$\log_{10}(\text{large wood export}) = 0.56 \log_{10}(\text{drainage area}) + 1.35 \quad (1)$$

equivalent to

$$\text{Large wood export} = 10^{1.35} \times \text{Drainage area}^{0.56} \quad (2)$$

We then used the best-fit equation to predict annual wood export from drainage area for 315 rivers flowing into an ocean (tables S2 and S3). To do this, we predicted the value of annual wood export and the 95% prediction interval for each of the 315 rivers and then summed the fitted values, upper bounds, and lower bounds of the predictions. The resulting estimated global wood flux to the oceans is 4.7 million m³/year (95% prediction interval range of 315,961 to 70,225,979 m³).

We also separately analyzed the two largest regional datasets, from Switzerland and from Japan, and used previously published relations between drainage area and wood export to estimate potential global wood flux (Supplementary Materials). The coefficients and exponents for the best-fit equations using only the Swiss or the Japanese sites are very similar to those in Eq. 2. Wood flux estimates using previously published relations range from 990,866 to 6.0 million m³ and thus fall within the 95% prediction interval range of our analysis.

DISCUSSION

Quantifications of the volume of downed wood stored in river corridors, typically conducted over limited lengths of a river, indicate an inverse relationship with drainage area, such that more wood is stored in the upper portions of watersheds (35, 36). This likely reflects the greater ability of larger rivers to transport wood pieces downstream (37). Wood pieces that are long relative to the width of the channel are more likely to be trapped and stored by features such as bars and islands or bankside vegetation, and this storage becomes increasingly important in smaller channels (38). Although wood recruitment, transport rates, decay, and storage vary between major global biomes (31, 35, 36), the ability of drainage area to represent approximately half of the variation in measured riverine wood fluxes in the dataset presented here is encouraging, considering the diversity of forest primary productivity, wood recruitment and transport processes, and land cover history and forest management within the calibration dataset. This diversity presumably causes the large range in the 95% prediction interval, from an estimated low value

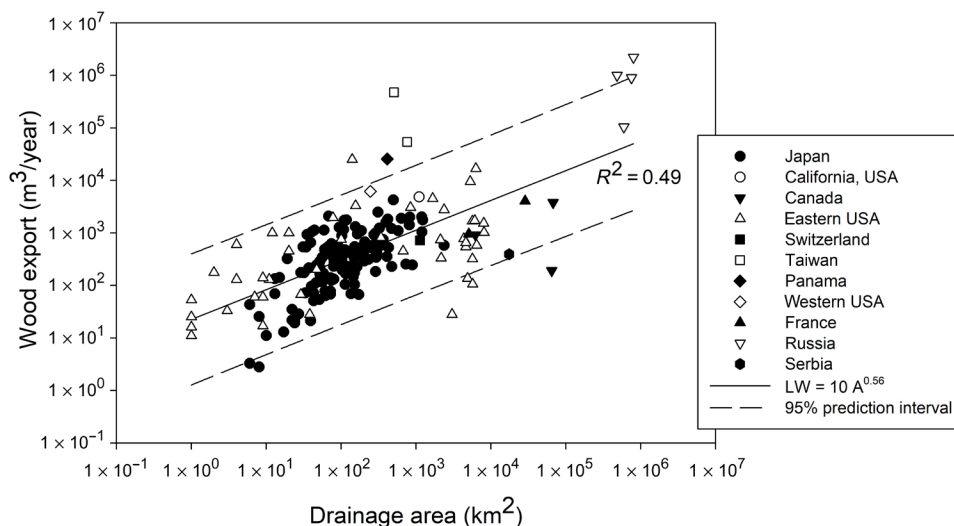


Fig. 1. Average annual and extreme-event wood export for the sites in table S1. The 95% prediction interval is indicated by the dashed lines. LW, large wood.

of $\sim 300,000 \text{ m}^3$ of wood flux to the oceans annually to an estimated high value of $\sim 70 \text{ million m}^3/\text{year}$.

The numerical estimate reported here represents contemporary wood fluxes on rivers draining areas of 6 to $797,385 \text{ km}^2$, whereas the drainage areas used to estimate potential global wood flux extend to a maximum of $4,014,500 \text{ km}^2$ for the Amazon River. The primary source of uncertainty is scaling of wood flux with drainage area—here, we present a linear relationship between the base 10 logarithms of drainage area and large wood export. Large rivers include extensive floodplains and numerous islands and bars that effectively trap and store wood moving downstream, which might reduce the wood flux per unit drainage area relative to smaller rivers. Three of the largest rivers in the calibration dataset of wood fluxes, however, have exceptionally high values of wood export that fall outside of the 95% prediction interval (Fig. 1). These are Siberian rivers. Boreal rivers of North America and Eurasia are known to export large quantities of wood to the Arctic Ocean (39, 40). The scaling of wood export at very large drainage areas from different forest biomes (i.e., boreal versus temperate versus tropical) is unknown, but the few large rivers on which wood export has been investigated tend to have relatively brief and infrequent episodes of substantial wood transport that account for much of the total wood exported from the basin over time spans of decades or longer (37, 41).

Part of the uncertainty in extrapolating the calibration dataset to larger drainage areas arises from differences in forest cover and wood recruitment within a very large drainage. When listing drainage areas in table S2, we did not include dryland rivers such as the Nile or the Orange that we inferred would not export wood to the oceans. We did include dryland rivers flowing through unforested lowlands if the rivers have forested headwaters and the potential to transport large wood all the way to the ocean (e.g., the Colorado River). (Although the Blue Nile has forested headwaters in Ethiopia, the extensive natural lakes and marshes of the middle and lower Nile would likely prevent wood export to the Mediterranean.)

Another part of the uncertainty in extrapolating the calibration dataset comes from differences in wood dynamics across biomes. Extremely fast rates of wood decay in the tropics (42) relative to temperate and boreal forests (6), for example, suggest that large wood fluxes from the tropics are dominated by episodic extreme events, such as those from Panama and Taiwan used in the calibration dataset. Very slow wood decay rates in the high latitudes could produce a more uniform wood flux through time, although boreal rivers are also characterized by uneven rates of wood transport to the ocean from year to year (39, 41). Given these uncertainties, we assume that the calibration dataset reflects interannual variability across biomes,

although this assumption could well prove incorrect as more data become available in future.

The estimated potential wood export to the oceans represents an upper bound for contemporary conditions but a lower bound for historical conditions (Fig. 2). The estimate is an upper bound for contemporary conditions because it reflects the maximum possible wood flux if all the wood moving into the world's rivers at present actually made it to the oceans, rather than being directly removed from rivers and reservoirs. Most of the wood fluxes in the calibration dataset come from reservoirs, and most wood that enters reservoirs is not allowed to continue downstream to the ocean. It is not feasible to quantitatively estimate the proportion of large wood recruited to river corridors globally that is removed in the context of river and reservoir management because these numbers, if recorded, are not publicly accessible for most regions of the world. In this context, however, it is useful to remember that only 23% of rivers longer than 1000 km flow uninterrupted to the ocean and that most of these rivers are in the Arctic and the Amazon and Congo basins (43).

The estimated potential wood export is a lower bound for historical conditions in that the values of wood export reflect contemporary forest cover, rather than the more extensive and generally older forests present before human-induced alteration of land cover associated with agriculture and industrialization. As noted above, global forest cover has declined by an estimated 12% since the development of agriculture. Only about 35% of what remains is primary forest (never cleared but subject to natural disturbances), and <1% of the Northern Hemisphere's temperate-latitude forests are considered primary (44). More extensive forest cover, especially in riparian areas, and older forests typically equate to greater wood recruitment to rivers (45, 46). It is not feasible to effectively constrain how much more wood might have been recruited to rivers historically because most understanding of differences in old-growth, primary, and managed forests is based on the volume of wood stored on the forest floor or in rivers [e.g., (46)], rather than on recruitment rates per year. In addition, the inferred changes in wood recruitment through time as a forest stand matures vary among different types of forest. Comparisons of volume of downed wood within a single forest type among forest stands of different ages suggest, however, that primary and old-growth forests commonly yield at least twice as much downed wood as managed and younger forests [e.g., (46, 47)]. The yield of large wood per unit drainage area was thus likely much greater in the historical past, and the upper 95% prediction interval from the calibration dataset ($\sim 70 \text{ million m}^3$ wood) might represent a reasonable estimate of wood flux to the ocean before intensive human alteration of global land cover and river networks.

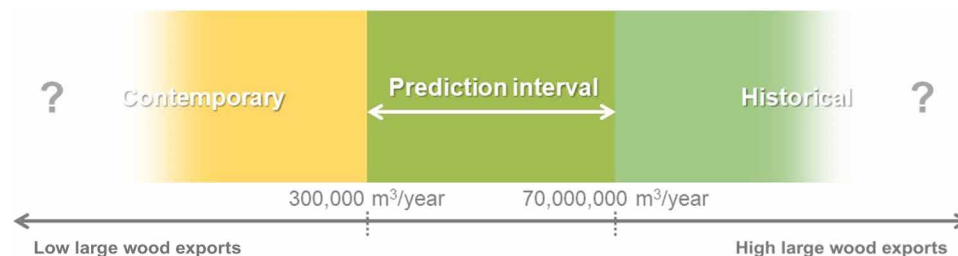


Fig. 2. Schematic illustration of the estimated upper and lower 95% prediction intervals for annual global fluxes of large wood to the oceans in the absence of wood trapping in reservoirs and removal from rivers.

The estimated wood export can also be compared to global estimates of biospheric particulate organic carbon fluxes to the oceans. Galy *et al.* (48) estimate a global export of 157 metric megatons each year. The density of wood varies widely by species but is mostly within the range of 300 to 900 kg/m³. Using an intermediate value of 600 kg/m³ and assuming that 50% of the wood is organic carbon, an annual wood export of 4.7 million m³ equates to 1.41 metric megatons of carbon export. This is a small percentage of estimated particulate organic carbon export, which seems reasonable even under natural conditions because of the much greater mobility of small particles of organic matter relative to large wood pieces. Again, the export of carbon in the form of large wood was likely much greater before human alteration of forests and river networks.

We hope that this simple analysis will spur efforts to quantitatively estimate wood flux to the oceans from the remaining relatively undammed large rivers such as the Mackenzie and Yukon in North America or the Amazon and Congo in the tropics. Although detection of individual wood pieces or masses of wood using remote sensing can be challenging (49), continuing enhancement of the spatial resolution and temporal frequency of various remote imagery systems will likely improve our ability to remotely quantify wood fluxes to the oceans.

We also hope that increasing recognition of the environmental benefits of large wood in coastal and marine environments will limit removal and destruction of driftwood on beaches and in nearshore areas and will encourage reservoir managers to consider how to bypass large wood rather than removing it from river networks altogether. Increasing recognition of the global extent of alteration of water (50, 51) and sediment (52, 53) fluxes to the oceans has encouraged the global community to think about the implications of these altered fluxes and about how to mitigate negative effects of reduced fluxes. We suggest that altered wood fluxes deserve the same attention.

MATERIALS AND METHODS

Experimental design

Our primary objective is to develop a first-order estimate of wood export to the oceans. This estimate is based on a limited dataset of measured wood export to reservoirs under average conditions and during extreme storms and estimated wood export to the ocean during extreme storms. The largest number of individual data points comes from Japan and Switzerland, and we initially analyzed these large regional subsets of the data. These analyses and results are presented in the Supplementary Materials. The entire dataset includes rivers in Canada, France, Japan, Panama, Russia, Switzerland, Taiwan, Panama, and the United States (California, Maryland, Pennsylvania, and Virginia) and thus represents a wide range of biomes, from boreal forests through temperate-zone forests to tropical rainforests. All data have been previously published and the original references and specific values used in these analyses are in table S1. The original estimates were developed in different ways. Most of the data used here were derived from wood accumulating in reservoirs, but those from (54) come from estimated export to the ocean.

We used R to develop a linear regression model of wood export based on drainage area. We then compiled drainage areas for rivers draining >2000 km² that flow directly into an ocean (table S2) and used these values with the linear regression to calculate 95% prediction intervals to estimate potential global wood export to the oceans in the absence of wood removal from river corridors.

The linear model fit with the log-transformed data has a prefactor of 1.35 (95% confidence interval, 1.15, 1.54; SE, 0.10) and an exponent of 0.56 (95% confidence interval, 0.48, 0.64; SE, 0.04). Both estimates from the model have $P < 0.0001$, indicating that the slope and intercept are statistically different from 0. The test of the full model versus the null model has $P < 0.0001$, indicating a significant linear relationship between the transformed data.

We also used previously published regression equations for wood export in relation to drainage area with the data in this paper to examine how sensitive the predictions of wood export are to the data used to develop the regression equation. These results are presented in the Supplementary Materials.

Statistical analysis

We used RStudio to conduct the statistical analysis (55). We log-transformed the calibration data of 194 points to align with the assumption of normally distributed data and fit a linear model with the `lm` function in base R stats package [$\log_{10}(\text{large wood export}) \sim \log_{10}(\text{drainage area})$]. We then used the `predict.lm` function in the stats package to predict the log of annual large wood export values (including upper and lower 95% prediction intervals) for 315 rivers. We back-transformed the predicted values and summed them to estimate the global annual wood flux to the oceans.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <https://science.org/doi/10.1126/sciadv.abj0988>

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Damming the wood falls

Ellen WohlEmily P. Iskin

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