Basin-scale land use impacts on world deltas: human vs natural forcings

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Abstract

A new global database of 86 deltas and river basins was analyzed to investigate the relative importance of deforestation and land use changes versus natural forcings in determining long-term total delta size. Results show that mean river flow and shelf slope were the most important variables, whereas population density and sediment load had a much lower importance. Deforestation and other variables related to land-use generally had a very small effect, but were more influential in a subset comprising Mediterranean and Black Sea deltas. As most deltas have developed over thousands of years, the much shorter-lived anthropogenic signals from deforestation and other landscape perturbations have had only secondary impact on the total area of deltas. Also, delta progradation is strongly influenced on sand deposition, whereas anthropogenic impacts on sediment load have more often impacted mostly the finer sediment being deposited offshore (prodelta deposits) or in the deltaic plain. These data disproves the hypothesis that delta size and growth is strongly influenced by human forcings, particularly for larger deltas, since Holocene delta building is mainly determined by natural forces. However, humans are influencing the geomorphology of deltas, particularly over the last century when the Anthropocene nature of deltas has become manifest. A more precise terminology is proposed to clarify concepts such as “human-made”, “human-engineered” or “human-influenced” deltas.

Introduction

Deltas are by definition sedimentary features, built by deposition of material eroded from river catchments in conjunction with *in situ* organic soil formation. There are many anthropogenic influences on sediment yield, including urbanization, deforestation, agricultural practices, mining, and the retention of sediment by reservoirs (Syvitski et al., 2005). Not surprisingly, therefore a growing number of studies have highlighted the anthropogenic alteration of fluvial sediment flux to the coast (Walling, 2006), and concluded that some deltas have prograded much faster or even formed during the late Holocene as a consequence of elevated sediment loads due to human activities (Syvitski and Kettner, 2011; Maselli and Trincardi, 2013) (see Table S1 for an expanded list of references). Deltas in Southeast Asia, the Mediterranean and Black Sea are considered the paradigm of human influence on delta geomorphology and growth, because of intense human activity within their basins over several millennia (Hori et al., 2001; Giosan et al., 2012). The Ebro, Rhone, Po and Danube deltas have been highlighted as "man-made" (Maselli and Trincardi, 2013; Guillén and Palanques, 1997).

The total size of a delta plain (subaerial delta), as defined by the extent of the delta fringe, is primarily determined by the amount of coarser sediment fraction (fine sand) delivered by the river, which in turn is dependent on river discharge (Syvitski and Saito, 2007; Giosan et al., 2014). The interplay of fluvial input with marine waves and currents controls the partitioning of sediment between subaerial and subaqueous portions of deltas (Swenson et al., 2005). Consequently, increased sediment delivery is believed to result in a faster delta progradation and larger delta size (Meade, 1996) and basins with long-term human-impacts (enhanced sediment flux) might be expected to have deltas proportionally larger than less impacted ones. However, the effect of increased fluvial sediment delivery on delta progradation depends on several factors, including granulometry. Thus, a smaller grain size increases the fraction of sediment delivered to the shallow marine area (the prodelta environment) and the extent of subaqueous delta progradation relative to subaerial delta development (Swenson et al., 2005). Moreover, the ratio of sediment delivery to river discharge differs among basins and is difficult to estimate (Walling, 1999; Notebaert et al., 2010). For example, large Asian river basins are often cited as examples of low sediment delivery ratios (Walling, 2006; Allison et al., 1998), but some of them have high human-induced sediment load (Saito et al, 2001; Shi et al., 2010). Such examples suggest that there is an apparent contradiction between estimates of sediment fluxes near the source and those at the sink, the so-called sediment delivery problem (Walling, 1999). Ultimately this is a question related to the cumulative influence of the 7,000 year history of the Holocene, compared to the recent history of the massive human-induced changes during the Anthropocene (Waters et al., 2016).

The mismatch between what is eroded from the basin, what is transported to the river mouth and what is deposited in the delta can be attributed to several factors: a) deforestation and land use change that do not always increase land erosion (Hamilton, 1987); b) most of the eroded sediment is deposited close to its source (Wilkinson and McElroy, 2007); c) coarser sediment transport involves a variable time-lag (10's to 1000's of years) from source to sink depending on basin size and slope (Meade, 1996); d) increased sediment load causes increases in deposition in the alluvial valley due to its buffering capacity (Walling, 2006); e) most of the increase in sediment load is fine sediment (silt-clay) unless river flow increases (Owens et al., 2005); f) an increased sediment load reaching the river mouth does not necessarily imply additional delta growth since fine sediment is deposited in the ocean (prodelta) or in the delta plain (aggradation) but does not contribute to delta fringe progradation (Orton and Reading, 1993); and g) dams retain a significant portion of the river sediment load, though large-scale damming is a relatively recent activity. Large dams store approximately 65 Gt/y, an Anthropocene magnitude that is many times the total load transported by rivers (Syvitski et al., 2005).

Furthermore, reliable long-term records of sediment load dynamics are scarce (Whol et al., 2015); and sediment record in deltas is often discontinuous; the limited C^{14} dates available indicate that deposition is highly heterogeneous across space and time (Cearreta et al., 2016). Consequently, it is difficult to test the contribution of land use changes on delta growth directly (i.e., via field data linking additional delta growth to additional sediment erosion and transport).

Here we take an indirect approach to assessing the contribution of natural forcings and land-use change to delta progradation, applying General Linear Models (GLMs) to a new database of world deltas to quantify the contribution of these forcings. We hypothtsized that no matter the changes in the rhythm of delta growth, the final result (delta size) would be different if human land-use changes have exacerbated sediment transport to the coast. We further hypothesized that if human effects at the watershed scale were important to delta growth, a proportionally larger delta size would be expected for river basins with a long history of human occupation and land clearing. We measured delta size as the area included in the external contour of the emergent delta as defined by the position of the delta fringe, so the conversion of marshes to open water in the delta plain because of sea level rise and sediment deficit (Giosan et al., 2014) or the draining of lagoons to create farmland are not considered in this analysis. We excluded from the analysis the effects of direct human impacts in the delta plain that could influence delta size, such as diking, artificial diversions of river distributaries, etc. Fourteen variables (out of 17) were selected (Table 2) from 86 deltas and their basins worldwide (Fig. 1) to evaluate the effect of watershed anthropogenic drivers versus climatic and physical drivers on delta size (the dependent variable) (See more details on methods and data sources on the corresponding section).

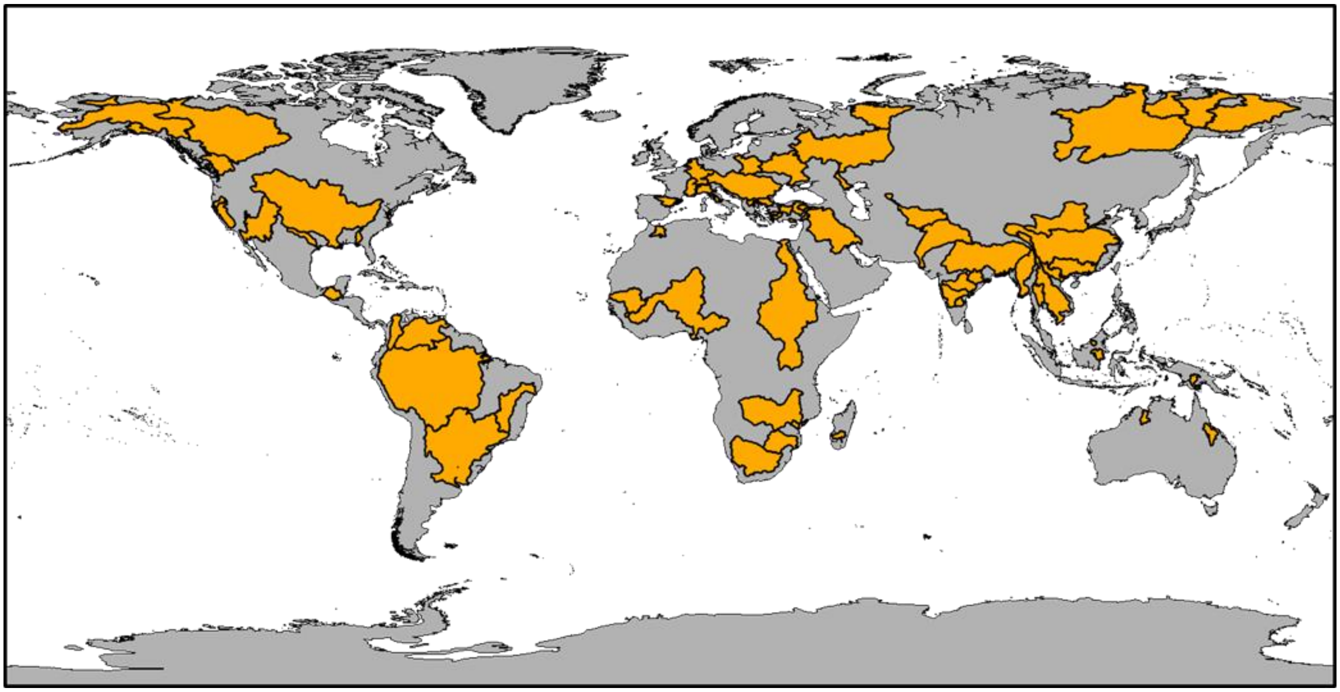

Figure 1. World map showing the river basins covered in the present study.

The new approach in this study is to include human-impact variables in the analysis together with geomorphic and climatic forcings, using the new global dataset of deltas and their river basins that is the most updated and complete to date. Another relevant contribution is the separate analysis of Mediterranean and Black Sea deltas to determine if a stronger signature of human impact on delta size is evident. We do not consider in the paper recent Anthropocene effects that have been more investigated (i.e., impact of dams), rather we address the long-term anthropic signature versus the geomorphic-climate signature on total delta size and sustainability.

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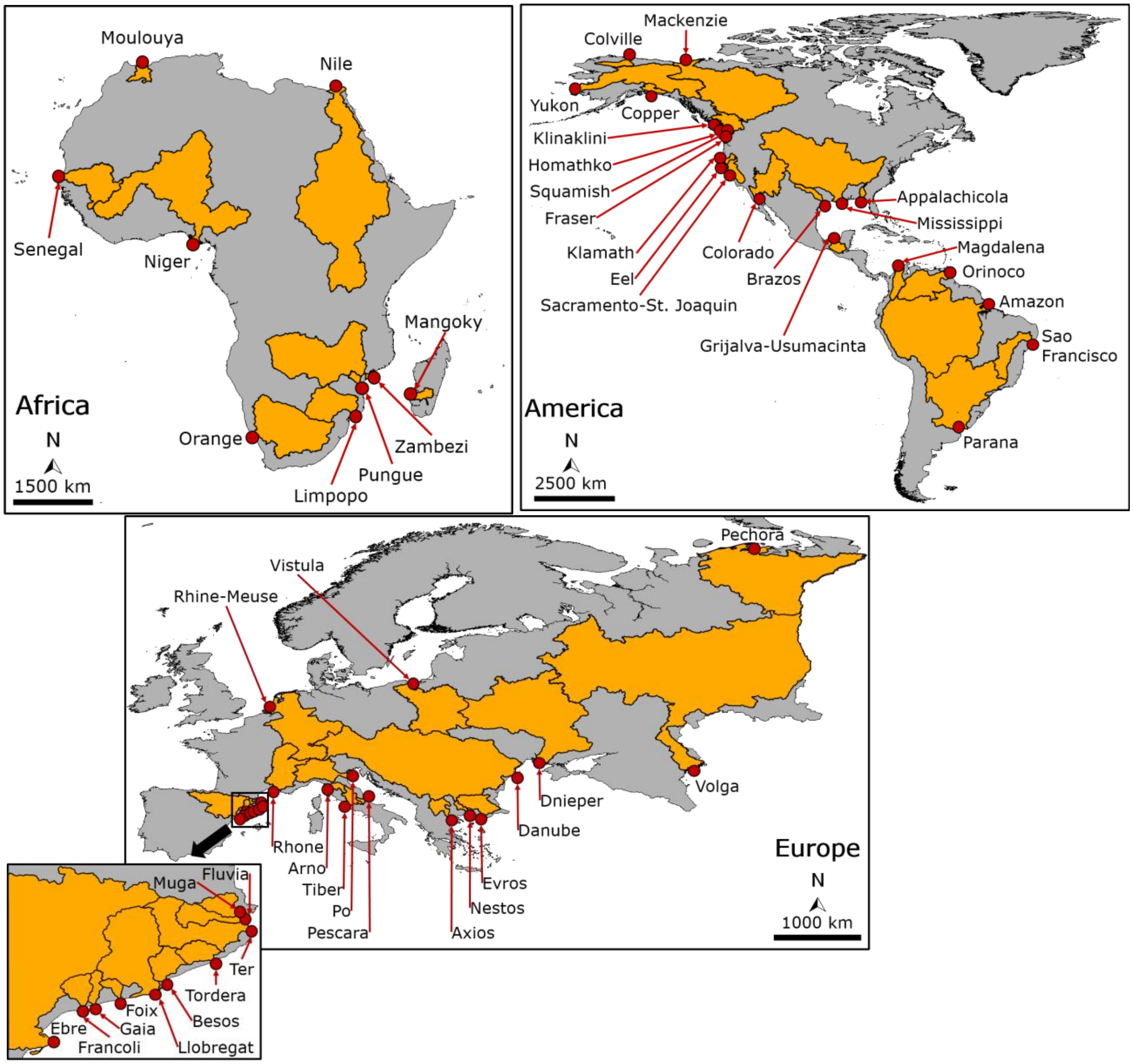

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Pungue
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Colville
Yukon
Copper
Klinaklini
Homathko
Squamish
Fraser
Klamath
Eel
Sacramento-St. Joaquin
Colorado
Brazos
Grijalva-Usumacinta
Appalachicola
Mississippi
Magdalena
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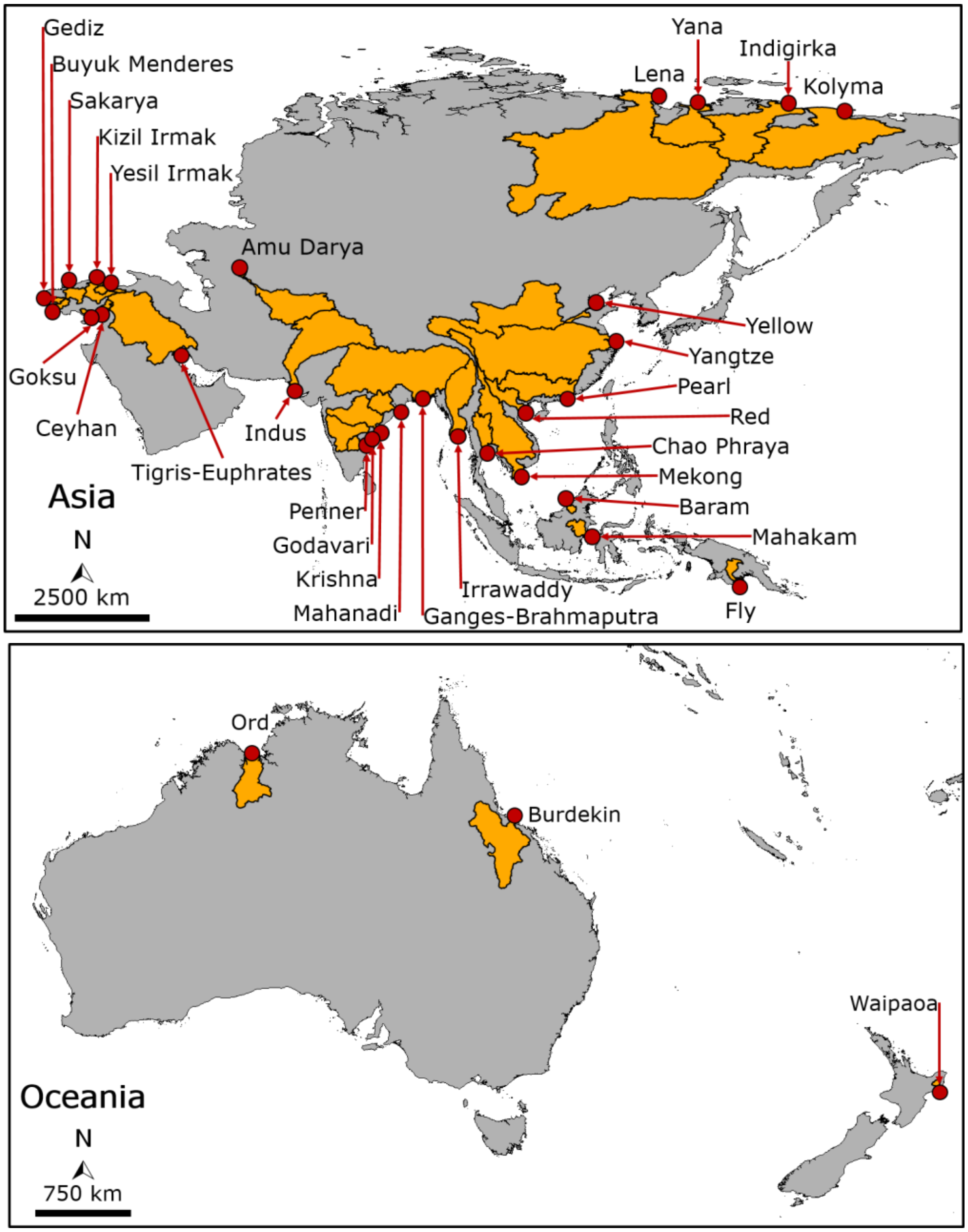

Figure 2. Maps showing the location and name of the studied deltas in the different continents.

Methods

Data collection

Data was gathered for 86 deltas worldwide (29 of them opening into the Mediterranean and Black Sea, named Med-Black deltas hereafter) by a systematic literature search of public databases, scientific papers, and reports available from national and international literature. The following groups of variables were initially considered for each delta: Location (latitude and longitude); size and elevation (delta and basin surface area, river length and elevation at source, river slope); mean river discharge, sediment load and sediment yield; mean rainfall; local marine features (tidal amplitude and continental shelf slope); basin indicators of human impact: population density, number of large cities, and number of dams; dam capacity; forest cover loss and present land use (forest, grassland, savanna, and scrubland, wetlands, croplands and irrigated croplands, urban-industrial, drylands). The variables, units and main sources of data collected are summarized in Table 1.

We selected almost all world deltas down to ca. 100 km^2 (smaller for some Med-Black deltas), excluding some cases for which available information was scarce. The final database used for the multivariate analysis included 14 variables, among which were basin area and slope, flow and sediment discharge, delta area, tidal range, shelf slope, land uses and vegetation cover, as well as other human impacts (see Table 1). To keep the number of dependent variables as low as possible to avoid excessive computing time (growing exponentially when one variable is added), three variables were excluded from the initial 17. Delta area were obtained from published works (e.g. Syvitski and Saito, 2007; Walker, 1998; Tockner et al., 2009; Kravtsova and Mit'kinykh, 2011) and the World Delta Database (Hart and Coleman, 2016). Measures from aerial photographs and maps were used to validate and solve inconsistencies among databases. Mean river flow and sediment load were obtained from global databases such as Lehner et al. (2008), Fekete et al. (2002), and the Global River Sediment Yields Database (FAO, 2008); where possible, the early values less influenced by human activities were used. Most of the independent variables were extracted from public GIS databases with the Spatial Analyst Tool in ArcGIS 9.3 (see Table 1 for source and resolution details), such as basin area, mean basin rainfall, mean population density in the year 2010, percent vegetation cover, and the human impact variables percent urban area, percent croplands, and percent forest deforestation. Mean basin slope was derived from the Global Multi-resolution Terrain Elevation Data 2010, and continental shelf slope (from the present river mouth to the outer limit of the shelf) from the General Bathymetric Chart of the Oceans (see Table 1). Tidal range was obtained from global long-term daily tidal charts, and dam capacity from the Global Reservoir and Dam Database; dam capacity was standardized by dividing capacity by basin area, thus obtaining relative dam capacity (Hm^3 km^{-2}).

Table 1. Description of the variables for the analysis of 86 worldwide deltas. Data sources in numbers are cited in the main text. Delta area (dependent variable) was analyzed as function of 14 independent variables (in bold) representing human and natural predictors.

Variable	Data acquisition	Source	Spatial Scale
Delta Area (km^2)	Bibliographic	Syvitski and Saito, 2007; Rakotomavo and Fromard, 2010; Walker, 1998; Tockner et al., 2009; Kravtsova and Mit’kinykh, 2011	

Basin Area (km^2)	Derived from GIS	Peucker-Ehrenbrink, 2009; Meybeck and Ragu, 2012; Weatherall et al., 2015	15 ARCSEC 30 ARCSEC 30 ARCSEC
Mean Basin Slope (φ)	Derived from GIS	Revenga, 2003	7.5 ARCSEC
Mean River Flow (m^3 s^{-1})	Global databases	Hart and Coleman, 2016; Lehner et al., 2008; Fekete et al., 2002	
Sediment Load (kg s^{-1})	Global databases	Hart and Coleman, 2016; Lehner et al., 2008; Fekete et al., 2002	
Tidal Range (m)	Global tidal charts		
Shelf Slope (φ)	Derived from GIS	Danielson and Gesch, 2011	30 ARCSEC
Mean Rainfall (mm)	GIS		30 ARCSEC
Dam Capacity Rate (Hm^3 km^{-2})	Derived from GIS	Lehner, 2011	
Mean Population Density (# km^{-2})	GIS	CIESIN, 2016	30 ARCSEC
Forest Cover (%)	GIS	ESA, 2016	7.5 ARCSEC
Grassland, Savanna & Shrubland Cover (%)	GIS	ESA, 2016	7.5 ARCSEC
Urban Areas Cover (%)	Derived from GIS	DOD/USAF/AFWA	30 ARCSEC
Croplands Cover (%)	GIS	ESA, 2016	7.5 ARCSEC
Deforestation (%)	GIS	UNEP-WCMC, 1998	5 ARCMIN
Drylands Cover (%)	GIS	Cherlet et al., 2015	30 ARCSEC
Percent Habitat Lost (%)	GIS	Hoekstra et al., 2010	30 ARCSEC
Mean Human Footprint	GIS	Venter et al., 2016	30 ARCSEC

Statistical analysis

The effects of key environmental factors on delta size were analyzed using General Linear Models (GLMs). An information-theoretical approach was applied to find the best approximating models (Burnham and Anderson, 2002). GLMs were built including all possible combinations of environmental features, excluding interactions, due to the large number of variables included. The degree of support of each candidate model was assessed with the second order Akaike Information Criterion (AICc), rescaled to obtain ΔAICc values (ΔAICc=AICc$_i$ − minimumAICc). Candidate models were defined following two additional criteria: due to the high correlation amongst the parameters, only models with a variance inflation factor (VIF) of ≤ 3 were considered, to avoid multicollinearity effects in regression models (Maggini et al., 2006); and model performance had to be significantly better than the null model (*i.e.* the model including only the intercept), as judged by a likelihood-ratio test (Whittingham et al., 2005). When the final set of candidate models is selected, models having ΔAICc values within 1–2 of the best model have the most substantial support, those within 4–7 have considerably less support, while models with ΔAICc > 10 have essentially no support and might be omitted from further consideration (Burnham and Anderson, 2002). No significant differences were observed when ΔAICc = 2 or ΔAICc = 7 were considered, and the latter was used as supporting criterion. The relative plausibility of each candidate model was assessed by calculating Akaike's weights (w_i), which range from 0 to 1, and can be interpreted as the probability that a given model is the best model in the candidate set. Because no model was clearly the best one (*i.e.* $w_i \geq 0.9$), we calculated model-average regression coefficients as the result of a weighted average (by model w_i) of the regression coefficients across all models in which a given variable is present. The relative importance of each independent variable was also calculated by the sum of w_i for all models in which a given variable occurs (Burnham and Anderson, 2002). The more relative importance the higher the values of selection probability (SP), which vary from 0 to 1. Model-averaged regression coefficients (β) were compared with those from the full model to assess the impact of model selection bias on parameter estimates (Maggini et al., 2006). Lower (in absolute value) parameter bias indicates greater concordance between averaged and full models (reference value 0.05; Genua-Olmedo et al. 2016). Higher positive or negative β coefficients (in absolute value) indicate a stronger influence of an independent variable for differentiating the response variable across all candidate models (Burnham and Anderson, 2002). For all of the candidate models residuals were normally distributed according the Shapiro–Francia normality test ($P \geq 0.25$). All statistical analyses were performed with R software version 3.3.2; the MuMIn 1.15.6 package was used for multi-model inference analysis and Nortest 1.0-4 was used for normality test analysis.

Results

Geomorphological and hydrological variables were most important in explaining delta size (Table 2), especially continental shelf slope and mean river flow, were present in all the selected models (SP= 1) and had the largest effect on the dependent variable (β = -2.07 and 0.84, respectively), followed by sediment load (SP= 0.63, β = 0.11) and mean population density (SP=0.56, β =0.15), both with a smaller effect. Mean rainfall and urban land cover had a small negative effect, whereas the effects of deforestation, forest cover, grassland cover, cropland cover, tidal range, dam capacity and basin slope were very small. However, the effect of deforestation, forest cover and cropland area were more significant for the case of Med-Black deltas, but still relatively small. Interestingly, mean rainfall showed a dual effect on delta size, being positive for Med-Black deltas and negative for the other deltas. The weighted average model selected 13 variables (out of 14), to predict delta size with a highly significant regression coefficient (Fig. 2). Results from heavily human occupied basins of the Mediterranean and Black Sea (Table 2, Figure S1) also showed a high regression coefficient between observed and predicted values of delta size (Fig. 2). This model selected a total of 11 variables, excluding sediment load, dam capacity and tidal range (Table 2). Interestingly, crop area and urban area were selected in all models (SP=1) but they showed a moderate and negative effect on delta size (β =-0.14 and -0.15, respectively), whereas forest cover and deforestation were selected in fewer models and showed a moderate positive effect (β =0.14 and 0.13, respectively). Physical variables such as basin area and river slope were included in most models and had the largest (positive) effect on delta size (β = 0.83 and 1.05, respectively). In contrast to the model for world deltas, Med-Black deltas show a very small influence of mean flow, shelf slope and population density. Overall, human influence on the size of these deltas is more significant than in world deltas, nevertheless physical and climatic drivers were the most influential. Noticeable, human impacts show opposite or contradictory influences, since the negative effect of cropland area and urban area on delta size counterbalance the positive effect of deforestation and forest cover (which one might have expected to have an opposite influence). The net effect is that Med-Black deltas do not appear to be a distinct group when plotted among the world deltas (Fig. 2), but they tend to be smaller, as shown by further analysis using a new variable labeling Med-Black Deltas (Table 2).

Table 2. Results from the information–theoretic framework analyses to evaluate the importance of independent variables on delta size: World Deltas (86); Med. Deltas (29 Med-Black Deltas); Non-Med. Deltas (57 World Deltas, excluding Med-Black Deltas); and World Deltas MD (86 World Deltas where Med-Black is included as factor). Model-averaged regression coefficients (β), selection probability (SP), parameter bias, number (N) of candidate models and correlation coefficient between observed and predicted values (r) are shown. Parameters included in the best

model are highlighted in grey. See *statistical analysis* for interpretation of model parameters (β, SP and Bias).

Model Term	**World Deltas** N **= 51,** r **= 0.92**			**Med. Deltas** N **= 8,** r **= 0.97**			**Non-Med. Deltas** N **= 144,** r **= 0.89**			**World Deltas MD** N **= 116,** r **= 0.92**		
	SP	***β***	**Bias**	***SP***	***β***	**Bias**	***SP***	***β***	**Bias**	***SP***	***β***	**Bias**
Intercept	1.000	1.044	0.476	1.000	-5.995	-0.412	1.000	0.868	0.240	1.000	1.159	0.428
Mean River Flow ($m^3 s^{-1}$)	1.000	0.837	0.212	0.145	0.121	0.329	1.000	0.910	0.099	1.000	0.794	0.266
Shelf Slope (φ)	1.000	-2.072	-0.041	0.116	-0.072	-2.299	1.000	-2.470	-0.128	1.000	-2.028	-0.031
Sediment Load (kg s^{-1})	0.634	0.111	0.040	*Not selected*			0.409	0.069	-0.636	0.701	0.135	0.014
Population (# km^{-2})	0.559	0.152	-0.605	0.079	0.042	-13.607	0.108	0.010	-1.767	0.569	0.152	-0.656
Rainfall (mm)	0.556	-0.267	0.333	0.394	1.068	0.358	0.422	-0.215	0.511	0.534	-0.261	0.412
Urban Areas (%)	0.544	-0.044	-0.709	1.000	-0.149	-0.869	0.056	0.000	-75.990	0.481	-0.037	-0.723
Deforestation (%)	0.379	0.018	-1.574	0.527	0.131	-0.863	0.588	0.042	-0.865	0.390	0.019	-1.564
Forest Cover (%)	0.112	-0.003	-6.899	0.664	0.139	-1.388	0.430	-0.034	-1.624	0.088	-0.002	-8.111
GSS (%)	0.105	-0.003	-21.911	0.058	-0.003	27.178	0.543	-0.040	-1.996	0.126	-0.003	-15.137
Croplands (%)	0.090	0.002	30.082	1.000	-0.140	0.119	0.259	0.013	4.871	0.123	0.004	10.797
Tidal Range (m)	0.084	-0.014	-12.140	*Not selected*			0.143	-0.047	-6.025	0.343	-0.169	-2.118
Dam Capacity ($Hm^3 km^{-2}$)	0.070	0.001	-1.152	*Not selected*			0.055	0.000	-68.924	0.072	0.001	-3.572
Basin Slope (φ)	0.063	-0.001	123.641	0.767	1.046	-0.227	0.226	0.091	-3.414	0.054	0.002	-154.444
Basin Area (km^2)	*Not selected*			0.855	0.827	-0.133	0.112	0.030	-3.897	*Not selected*		
Med-Black Delta										0.558	-0.191	-1.232

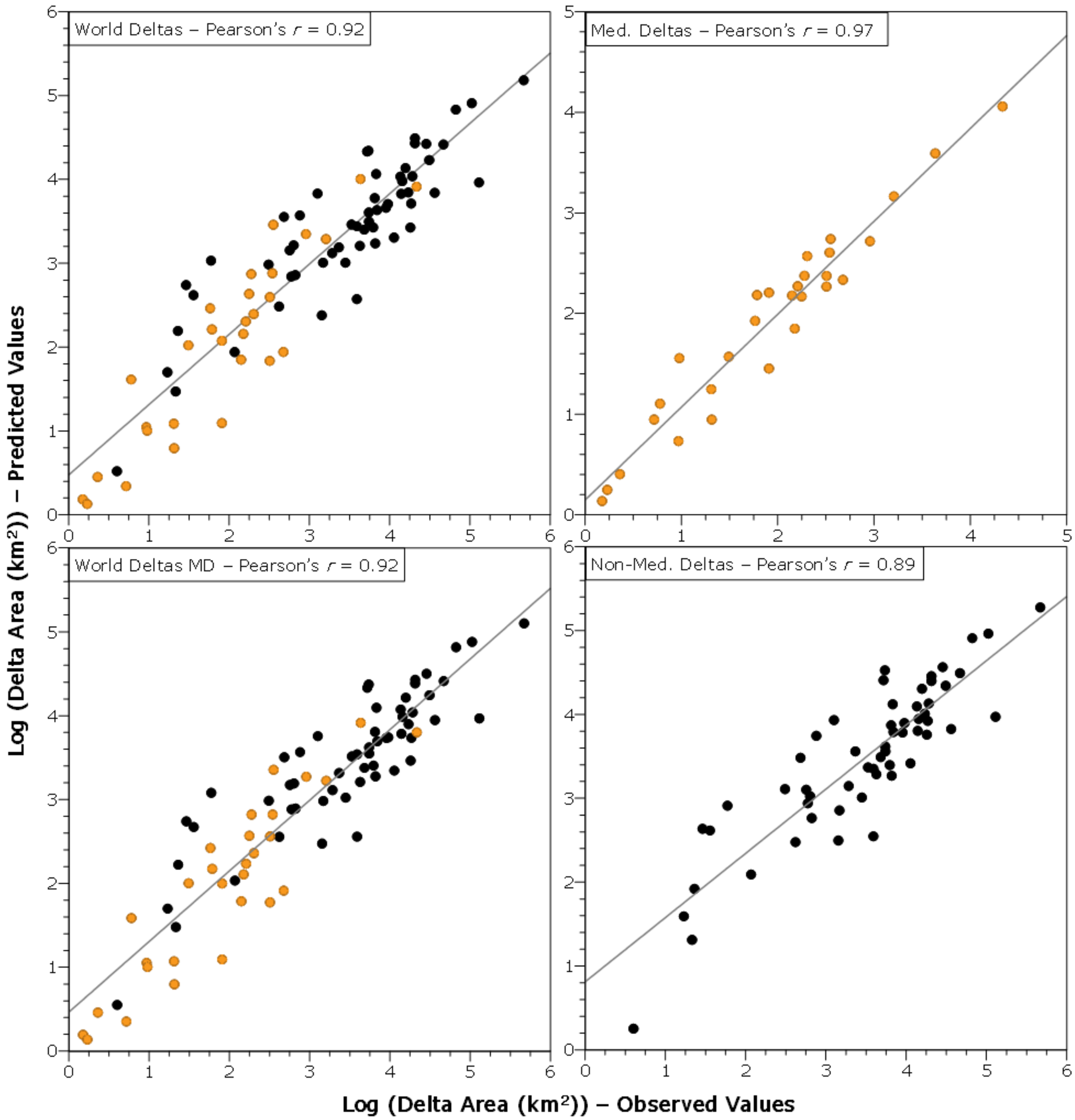

Figure 2. Regression plots of World Deltas, Med-Black Deltas, World Deltas including Med-Black Deltas as a variable, and Non-Mediterranean Deltas, showing the Pearson's Correlation coefficients (*r*) of predicted versus observed values of the dependent variable (delta size) obtained from the General Linear Models (GLMs). Med-Black Deltas are shown in yellow color.

Discussion

Results clearly show that the main drivers of delta size at the watershed level are strongly related to the hydrology (climate), and the morphology of the river basin and the continental shelf. A previous study by Syvitski and Saito (2007) also found river discharge to be the main explanatory variable of delta area, by using a scaling model including average discharge of its feeder river, the total sediment load, and the shelf depth (R^2 =0.91, 0% bias). In contrast, total sediment load has a small effect in the model presented here, likely because land-use variables are explicitly included in the analysis. Population density was found to be the most important among the anthropogenic variables for the case of world deltas; (see also Syvitski and Milliman, 2007). Population density integrates several aspects of human interference in river basin hydrology and sedimentary processes. Population density is often related to deforestation rates Maselli and Trincardi, 2013) and to a larger area devoted to farmland and urban areas. Perhaps the reason population density is more important than other anthropogenic variables is that it captures the interference of human activities on the alluvial valley and river hydro-sedimentology. Aside from the more recent (20th century) effect of dams, which is not having a significant effect on total delta size yet, the long-term alteration of the river course and its floodplain such as narrowing and dredging, straightening of meanders, construction of levees, occupation of the flood plain and the delta plain, among others, are reported to have a significant impact on sediment transport and the buffering capacity of the flood plain; such as the case of river basins undergoing millennial human occupation (Hori et al., 2001).

In general, results concerning world deltas and deltas other than Med-Black ones are more consistent and clearer than those obtained for the Med-Black deltas. The main reason is likely related to the small number of study cases (29) in relation to the analyzed variables (14), leading also to a stronger influence of outliers; so we think the results of this subset must be interpreted with more caution than those from the whole data set.

Contrary to world deltas, mean river flow and shelf slope are not important in explaining Med-Black delta size. Here the variables having more influence on delta size are rainfall, basin slope and basin area (again natural variables), whereas cropland area and urban area are the human variables with more influence but with much lower model-averaged regression coefficients (i.e. less influence on delta size). One possible explanation is that Mediterranean river flow regime is flashier and has been strongly modified from long ago, so in this case mean river flow is not so relevant to explain the capacity of sediment transport to the coast (and the consequent delta growth). This may explain why basin slope and area, together with rainfall have a larger influence in Med-Black deltas, and why sediment load is not selected by the model. Also in contrast with world deltas, shelf slope is not important in determining Med-Black delta size, possibly because the slope is more homogeneous among deltas. The negative effect of mean rainfall on delta size for the case of world deltas is more difficult to explain; one possible interpretation is that rainier river basins tend to have more regular flow regimes (proportionally less flashy).

The small effect of deforestation and other land use changes on delta size is likely related to erosion and sediment delivery to the coast being buffered in space and time within the basin, the so called “sediment delivery problem” (Walling, 1999). The relatively more important role of deforestation in Med-Black deltas could be explained because land clearing took place earlier and the river basins are smaller (and with higher slope) than the world average. Many larger river basins and deltas reflect long-term Holocene forces, where it is more difficult and takes longer for hinterland perturbations to be manifested as coastal deposits (Syvitski and Milliman, 2007).

The large discrepancy between cropland soil losses estimated from field studies and modelling (~75 Gt/yr) and sediment fluxes in rivers (~21 Gt/yr) is mostly explained by the deposition of most eroded material immediately adjacent to its source; only 2% of the terrestrial surface of the Earth is apparently enough to accumulate the sediment eroded from the remaining 35% devoted to farmland (Wilkinson and McElroy, 2007). For example, a study in SE Minnesota (USA) estimated that 47 to 65% of all sediment eroded in the past 137 years has moved no farther than 3 or 4 km (Beach, 1994). Another study in an area of the Magdalena river basin (Colombian Andes) undergoing severe recent deforestation (241% increase) resulted in a 33% increase in erosion rates that has translated into an increase of only 9% in total river sediment load (Restrepo et al., 2015).

Moreover, subaerial delta progradation is mostly dependent on sand deposition (Nittrouer and Viparelli, 2014) and subaqueous delta progradation is favored with a higher proportion of finer sediment (Swenson et al. 2005), so the increase in sediment load due to human activity mostly leads to an increase in fine sediment, which may be transported offshore in a large proportion (Giosan et al., 2014; Orton and Reading, 1993) or deposited in delta plain wetlands (Day et al., 2007). However, progradation rates of the subaerial and subaqueous deltas may differ considerably besides grain size effects, since they are also influenced by the frequency and magnitude of coastal storms, as well as by river discharge and flood frequency (Swenson et al. 2005). Therefore, deltas that prograde into low-energy marine environments fed by high-energy rivers should be those in which delta size would be more influenced by an increase of fine sediment inputs due to human alteration of the watershed.

Study results and existing literature do not suggest that the well documented anthropic increase in sediment delivery to the coast has caused in most of cases a significant additional delta progradation (higher than natural rates). In the Waipaoa River (New Zealand) sediment load increased more than 6 times due to deforestation (Kettner et al., 2007) primarily being mud, whereas delta progradation was largely controlled by sand; net accumulation of mud occurs behind the prograding sandy shoreface (Wolinsky et al., 2010). In the Irrawaddy (Myanmar), since 1850 less than 9% of the sediment load delivered to the delta has contributed to the observed progradation (Hedley et al., 2010), while in the Mekong Delta (Vietnam) the rate of delta front migration and stable sediment discharge during the last 3000 years indicate that a large increase in sediment discharge due to human activities did not occur in this typical Southeast Asian river (Ta et al., 2002). The subaerial delta of the Ganges-Brahmaputra is prograding very slowly relative to its subaqueous delta (Allison, 1998), and regions of the Amazon delta shoreface are eroding concomitant with rapid progradation of its subaqueous delta (Nittrouer et al., 1996). A recent paper showed that the reduction in sediment supply to the Mekong Delta is likely due to a shift in the tropical cyclone activity (Darby et al., 2016).

The recent increase in dam building is certainly affecting delta growth, but significant changes in delta size (in relation to total surface) may take longer to manifest. Although dam construction has dramatically reduced sediment fluxes to the coast (Syvitski et al., 2005), our results show no effect of dam capacity on delta size possibly because it is a recent effect that is not significant yet in global terms. However, in some river basins (especially in developing countries) the near synchronicity of dam building with deforestation and other land use changes limits the impact of upstream sediment load increases and could in part explain the small effect of land use changes on delta size.

Recent studies in the Ebro Delta, considered a typical example of "man-made" delta (Maselli and Trincardi, 2013), suggest that there has not been a large increase in sediment delivery and delta growth due to human activities. The long-term increase in sediment load of the lower Ebro River due to deforestation and human occupation of the basin has now been estimated at around 40% (Xing et al., 2014), rather than the 8-fold increase suggested previously (Walling, 2006). The former study (Xing et al., 2014) also showed that the background sediment load of the Ebro River under low impact conditions (4000 years before present) was already high (30 million tones yr^{-1}). Another study (Cearreta et al., 2016) has dated the origin of the present Ebro Delta back to the Early Holocene, not to the Late Holocene (Maselli and Trincardi, 2013; Guillén and Palanques, 1997) contradicting the hypothesis of the Ebro as "man-made" due to watershed deforestation.

Results suggest that similar conclusions may hold for other Mediterranean and Asian deltas, which have a long history of human influence but have not been created as consequence of river basin land use changes. We propose that the concept of "human-made delta" should be used only for the case of new deltas totally (or almost totally) created by human alteration of the river basin greatly increasing sediment load. One of the few known candidates is the Mangoky Delta in Madagascar, where the river mouth quickly prograded in the last 30 yr due to heavy deforestation in the hinterland (Rakotomavo and Fromard, 2010). These cases essentially may occur in the context of tropical river basins with heavy rains, high relief and highly erodible soils. We consider human-made deltas as extreme examples of "human-influenced deltas", which are those in which their size, shape and other geomorphological features have been altered by changes in the sediment flux due to land use changes in the watershed. This is the case for most of the world's deltas, except pristine deltas which are scarce nowadays. Then there is the case of "human-engineered deltas", those modified by the action of humans within the delta itself, mostly due to diversion or diking of the river distributaries and the delta plain; good examples of heavily engineered deltas are those of the Po and Yellow Rivers. In those cases deltas existed under pristine conditions, but they were smaller, with a different shape, in a different place, etc. Indeed, human-made large river diversions can create "man-made delta lobes" (as is the case of the new Yellow Delta), since the human deviation of the river far away of the previous mouth creates a new delta lobe that is not overlapping with the previous one.

Conclusions

This paper sheds light on the debate about the Anthropocene and the idea that some deltas have formed or are much larger because of the human alteration of the river basin that leads to an increase in sediment delivery to the coast. Some authors have even coined the concept of "man-made deltas" and argued that Mediterranean deltas were mainly formed due to human alteration of the basin. Our results contradict the idea of human-made deltas since delta size is essentially determined by natural forcings, even in Mediterranean deltas.

One of the findings of special interest is the weak signature of deforestation on delta size. Obviously human activity has increased the flux of sediments through land use changes (or in some cases, to reduce it), but we argue that it is mostly fine sediments that contribute little to delta progradation unless it is accompanied by a change in river flow that increases the capacity of the river to transport sand. This is not to underestimate the adverse effects of human activities on deltas, by development and reclamation, and by degradation of delta plain wetlands through prevention of sediments reaching the delta plain due to levee and dam construction. A more precise terminology is proposed to clarify concepts such as "human-made", "human-engineered" or "human-influenced" deltas.

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Data availability

All the original data are of public access and sources can be found in Table 1 (see references). The analyzed database is available as supporting information.

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Author contributions

C. Ibáñez is the lead author and contributed to writing the paper; C. Alcaraz built most of the database, did the statistical analyses and contributed to the Material and Methods; N. Caiola contributed to writing the paper; P. Prado contributed to the database and statistical analysis; R. Trobajo contributed to the database and reviewed some parts of the paper; X. Benito contributed to the database and reviewed some parts of the paper; J.W. Day, E. Reyes and J.P.M. Syvitski contributed to writing and reviewing the paper.