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Key Points:

- Model of river delta response to sea level rise and river sediment applied to 6,402 deltas and tested against land area change observations
- Projections suggest net delta land loss for GMSLR >5.5 mm/yr, and for RSLR under IPCC RCP4.5 and RCP8.5 by 2100
- Climate-change driven sea-level rise will likely exceed the effects of dams and subsidence on global delta land loss by 2100

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Projections of Global Delta Land Loss From Sea-Level Rise in the 21st Century

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Abstract River deltas will likely experience significant land loss because of relative sea-level rise (RSLR), but predictions have not been tested against observations. Here, we use global data of RSLR and river sediment supply to build a model of delta response to RSLR for 6,402 deltas, representing 86% of global delta land. We validate this model against delta land area change observations from 1985–2015, and project future land area change for IPCC RSLR scenarios. For 2100, we find widely ranging delta scenarios, from +94 ± 125 (2 s.d.) km^2 yr^{-1} for representative concentration pathway (RCP) 2.6 to −1,026 ± 281 km^2 yr^{-1} for RCP8.5. River dams, subsidence, and sea-level rise have had a comparable influence on reduced delta growth over the past decades, but if we follow RCP8.5 to 2100, more than 85% of delta land loss will be caused by climate-change driven sea-level rise, resulting in a loss of ∼5% of global delta land.

Plain Language Summary River deltas can erode and lose land from sea-level rise. Here we make model predictions of the effects of sea-level rise for global delta land area change up to 2100. Our model is validated against observations of delta land area change from 1985–2015. For 2100, we find that most climate change scenarios lead to net delta land loss. Worst-case scenarios for 2100 lead to a global river delta land loss of ∼5% of delta land, at a rate of 1,000 km^2 per year.

1. Introduction

River deltas are low-lying coastal landforms created by fluvial sediment deposition. Delta shorelines can retreat landward through relative sea-level rise (RSLR) but also advance seaward through sedimentation and delta plain aggradation. These dynamics are widely acknowledged and observed in the field (Blum & Törnqvist, 2000; Helland-Hansen, 1996), in experiments (Kim et al., 2006, 2009; Lai & Capart, 2009; Muto, 2001), and in numerical simulations (W. Anderson et al., 2019; Fagherazzi & Overeem, 2007; Hoogendoorn et al., 2008; Swenson, 2005).

Currently, however, many projections of future coastal and delta change from RSLR follow a so-called "bath-tub" or passive flood mapping approach (Hinkel et al., 2014; Kulp & Strauss, 2019; Ward et al., 2020). The bath-tub approach offers high spatial detail but ignores erosion and sedimentation (Anderson et al., 2018), which is particularly relevant for river deltas. The potential deviation between bath-tub estimates and true coastal change is evident from a global analysis that shows that deltas have gained land in recent decades despite sea-level rise (Nienhuis et al., 2020). An additional challenge is that of validation (French et al., 2016). Many projections of coastal and delta change for future RSLR (e.g., Schuerch et al., 2018; Vousdoukas et al., 2020) have not been tested against observations based on past RSLR.

From a theoretical perspective, delta morphodynamics can be viewed as a balance between fluvial sediment supply and RSLR. Fluvial sediment delivered to a delta is partitioned between delta plain aggradation, shoreline progradation, and losses further offshore (Blum & Törnqvist, 2000; Kim et al., 2006; Lorenzo-Trueba et al., 2009) (Figures 1a and 1b). RSLR and/or delta progradation creates accommodation space on the delta plain that traps fluvial sediment. Fast RSLR can force a scenario of delta retreat if all sediment is deposited on the delta plain and no sediment is left to supply the delta shoreline. Similarly, reductions in fluvial sediment supply to river deltas, resulting from e.g., dams (Dunn et al., 2019) or sand mining (Hackney et al., 2020), can decrease natural delta land gain rates (Besset et al., 2019; Nienhuis et al., 2020).

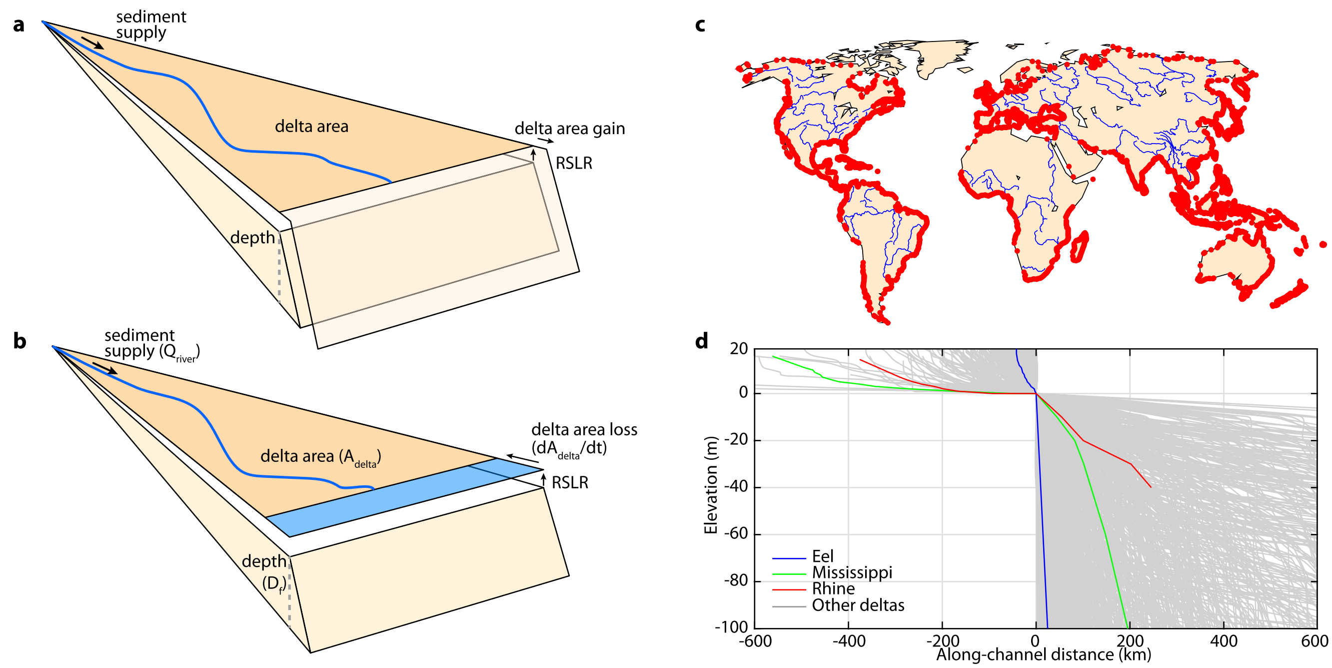

Figure 1. Delta profile response to relative sea-level rise. Model schematization for (a) delta land gain, and (b) delta land loss, including notation used in Equation 1, and (c) locations of deltas, and (d) longitudinal profiles of 6,402 coastal deltas included in this study.

The objective of this study is to apply first-order delta morphodynamic principles to make improved projections of future delta change under RSLR that are compared against historical observations. Our projections consider various IPCC representative concentration pathway (RCP) scenarios for sea level rise to 2100 and assume modern-day subsidence and fluvial sediment supply rates. We use a broad definition of deltas, including coastal river deposits sometimes referred to as estuaries or strandplains, and apply our methods on a global scale. This allows us to compare delta dynamics under a wide range of RSLR and fluvial sediment supply conditions and investigate drivers and trends that would be obscured in studies considering only a single delta.

2. Methods

We have developed a simple morphodynamic model to project land area change of 6,402 deltas (Figure 1c) for various sea-level rise scenarios. Our model compares fluvial sediment supply against local subsidence and sea-level rise, which together constitute RSLR. Based on the present-day delta area, we follow a morpho-kinematic approach (Wolinsky, 2009) to predict delta land loss (Figure 1a) or gain (Figure 1b),

$$\frac{dA_{delta}}{dt} = \frac{f_r \cdot Q_{river} - \frac{1}{2} A_{delta} \cdot RSLR}{D_f}, \quad (1)$$

where A_{delta} is the river delta area (m^2), dA_{delta}/dt is the change in river delta area ($m^2\ yr^{-1}$), Q_{river} is the fluvial sediment flux ($m^3\ yr^{-1}$), f_r is the fraction of the fluvial sediment retained in the delta profile, $RSLR$ is the relative sea level rise rate ($m\ yr^{-1}$), and D_f is the delta foreset depth (m). The fraction ½ arises from our triangular approximation of delta area (Figure 1). Shoreline changes scale with delta width at the shoreline, whereas the average delta width between the apex and the shoreline is half that amount.

Our model is one of the simplest possible models for delta change that includes its two main drivers, base level change (RSLR) and fluvial sediment supply. We apply it as a time-independent model, where changes are instantaneous and do not compound (i.e., delta area is not updated at a next timestep). We ignore delta land gain along the upstream boundary in our assessment of delta land area change because it constitutes land conversion from existing (albeit non-deltaic) land. We apply this model to 6,402 deltas, a subset from

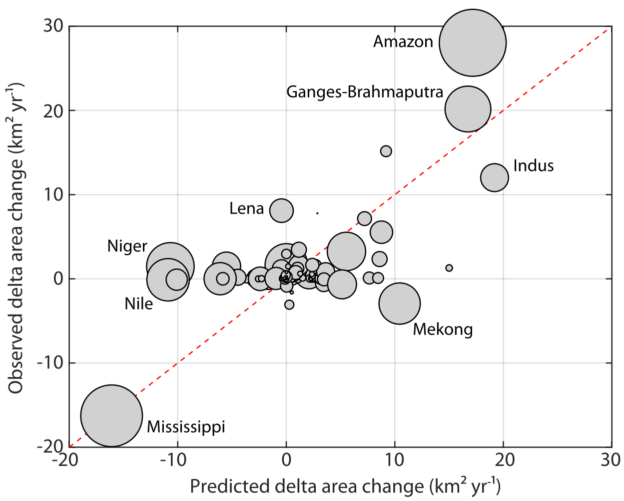

Figure 2. Predicted versus observed delta area change for individual deltas, where the marker size scales with the fluvial sediment flux.

Nienhuis et al. (2020), because of additional requirements to delta morphology further specified in the supplemental materials.

We retrieve global suspended load fluvial sediment supply for 6,402 deltas from WBMSed (Cohen et al., 2014; Nienhuis et al., 2020) and convert it to a depositional sediment flux using a bulk density (1,600 kg m^{-3}). WBMSed considers two fluvial sediment scenarios, pristine (Q^{p}_{river}) and disturbed (Q^{d}_{river}), that represent historic (before human impact) and modern conditions, respectively. For our future projections of delta change we assume modern, disturbed fluvial sediment supply conditions.

We estimate delta area as a triangle defined by the delta apex and its lateral shoreline extent. For 1,081 large deltas that represent 81% of global delta area, we use the manually collected delta apex and shoreline extent from Edmonds et al. (2020). We extend our data set beyond these to include a wide range of morphologies, RSLR rates, and local environments. For 5,321 other, mostly smaller deltas, we estimate the lateral shoreline extent using the delta area proxy from Syvitski and Saito (2007), and we estimate the delta length (shoreline to delta–basement transition) from its sedimentary wedge by fitting a basement cross-sectional profile under SRTM15+ elevation data (Figure 1d). We use the depth of the basement profile under the modern river mouth as a measure of the delta foreset depth (D_f).

We obtain measures of RSLR from various sources. For historic conditions, we use regional (1°) sea-level reconstructions from 1985–2015 (Dangendorf et al., 2019) combined with local vertical land movement (uplift, subsidence) observations based on GPS stations nearest to each delta (Blewitt et al., 2018; Shirzaei et al., 2021). For future projections (2007–2100), we use IPCC SROCC scenarios for RCP2.6, 4.5, and 8.5 (Oppenheimer et al., 2019) and assume land subsidence remains unchanged from their modern rates.

We assess model and data uncertainty by means of a Monte Carlo method and a sensitivity analysis, further details can be found in the supplementary materials. Model data and code necessary to reproduce the results are freely available online.

2.1. Test Against Observations

We test our morphodynamic model against observed delta area change from 1985–2015, using the average of two global land-water change models (Donchyts et al., 2016; Pekel et al., 2016). Both models are based on Landsat 30 m imagery (NASA, 2020) and are processed in the Google Earth Engine environment (Gorelick et al., 2017); we sum the outcomes within individual delta area extents for 6,402 deltas as defined by Nienhuis et al. (2020). We find that our delta area change predictions are generally in the correct order of magnitude (Figure 2), and that it explains a substantial fraction ($R2 = 0.39$, MSRD = 0.6 km^2 yr^{-1}) of observed delta land loss and land gain. Part of the past trend might still be too small to be explained by the two processes captured in our model. Land area change observations are also uncertain. Overall, there is positive bias in our global land change predictions when we use a sediment fraction retained (f_r) of one, predicting a net gain of 330 km^2 yr^{-1} versus observations of 196 km^2 yr^{-1}. For our future projections we use $f_r = 0.9$ to more closely match observed and predicted global net land gain for the period 1985–2015.

2.2. Predictions of Future Delta Change

Future deltas will generally experience increased RSLR rates (Figure 3a), with implications for delta area change. Assuming a globally constant RSLR and modern fluvial sediment supply, we find that global deltas gain land for a RSLR rate below ~5.5 mm yr^{-1} (Figure 3b). Global delta land area will decrease if that rate is exceeded.

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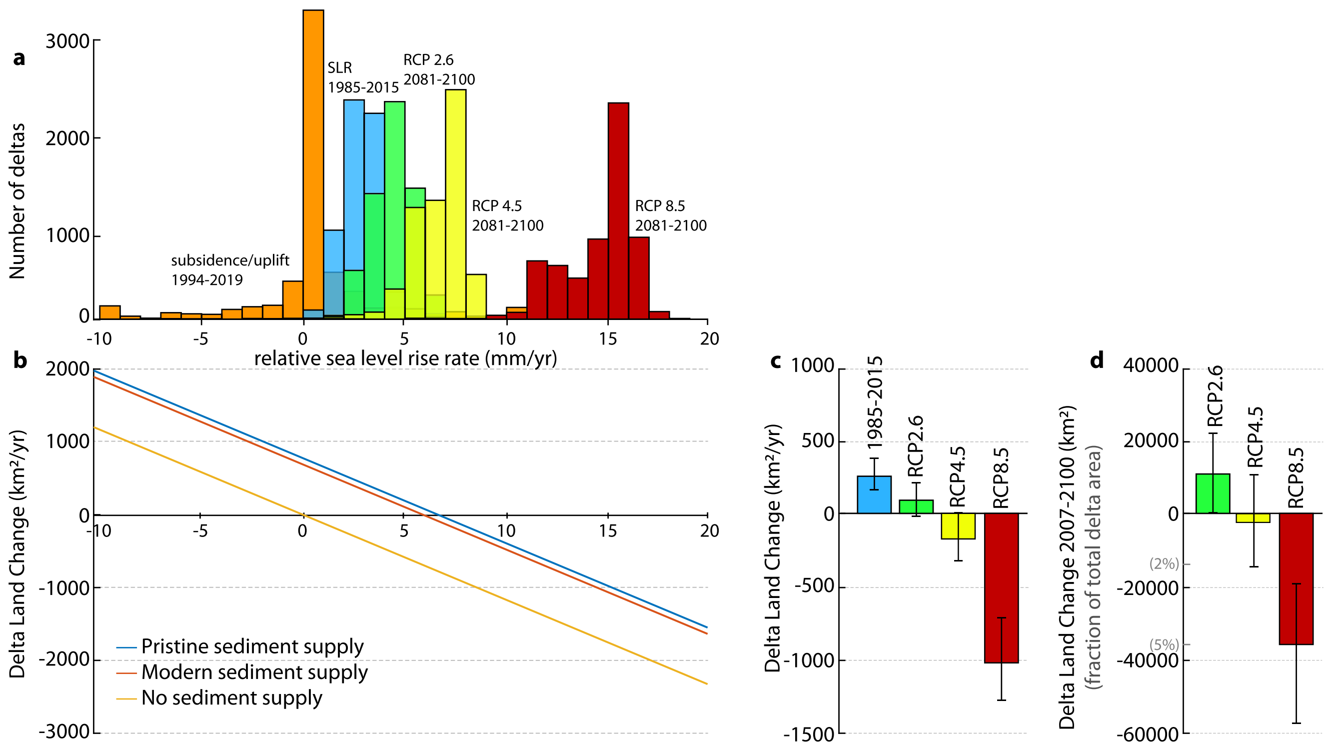

Figure 3. Effect of sea-level rise on delta land change. (a) Histogram of subsidence and sea-level rise rates for all coastal deltas (Dangendorf et al., 2019; Oppenheimer et al., 2019; Shirzaei et al., 2021). Note that subsidence extends beyond the axis range, in part because these data are not available for most deltas. (b) Effect of sea-level rise rates on global delta land change for various fluvial sediment supply scenarios. (c) and (d) Land area change of all coastal deltas for past and projected relative sea-level rise, including subsidence for (c) 2081–2100 and (d) cumulative from 2007–2100.

Delta area change is also affected by modifications to the fluvial sediment supply. Comparing modern supply against pristine (before river dams or deforestation [Cohen et al., 2014]) conditions, we find that the global change in sediment fluxes have had a small but noticeable effect (Figure 3b). Without anthropogenic modifications to the sediment supply feeding deltas, the threshold for net global delta land loss would have been 6.5 mm yr^{-1}. The comparative effect of fluvial sediment supply changes to global deltas can be further appreciated by a back-of-the envelope calculation: the global human-induced fluvial sediment flux reduction (1.4 BT/yr, Syvitski et al, 2005) distributed across all global deltas (850,000 sq. km, Edmonds et al., 2020) is equivalent to ~1 mm yr^{-1} of RSLR ($1.4 \cdot 10^{12}$/ $1600/850 \cdot 10^{9}$). This modest effect is partially because deforestation cancels out river dams on this global scale–resulting trends for individual deltas vary considerably.

In the limit of no fluvial sediment supply, our model predictions simplify to gradual upslope delta migration, with the slope given by the delta foreset depth over delta length (Figure 3b). Such projections would estimate delta land loss of −440 km^2 yr^{-1} for 1985–2015, contrasting observed delta land gain of +196 km^2 yr^{-1}.

Future RSLR will vary regionally and depends on the RCP scenario. Following the recent SROCC projections for sea-level rise under RCP8.5 (Oppenheimer et al., 2019) and assuming fluvial sediment supply and subsidence rates remain unchanged, we find global delta land loss rates of 1,026 ± 281 km^2 yr^{-1} (2 s.d.) by the end of the century (2081–2100). Cumulative since 2007 to 2100, sea level rise under RCP8.5 will lead to the disappearance of about 37,178 ± 17,919 km^2 (2 s.d.) of deltaic land–equal to about 5% of total delta area.

Projected land area change will vary between deltas (Figure 4). Despite the general trend of increasing land loss for higher RSLR, the specific RSLR threshold that triggers a delta into land loss is highly variable. Some deltas are projected to sustain growth under all RCP scenarios. Low-gradient mega-deltas are more sensitive to RSLR, the rapid land gain observed in Southeast Asia and South America (Nienhuis et al., 2020) will diminish under all RCP scenarios (Figures 4b–4d).

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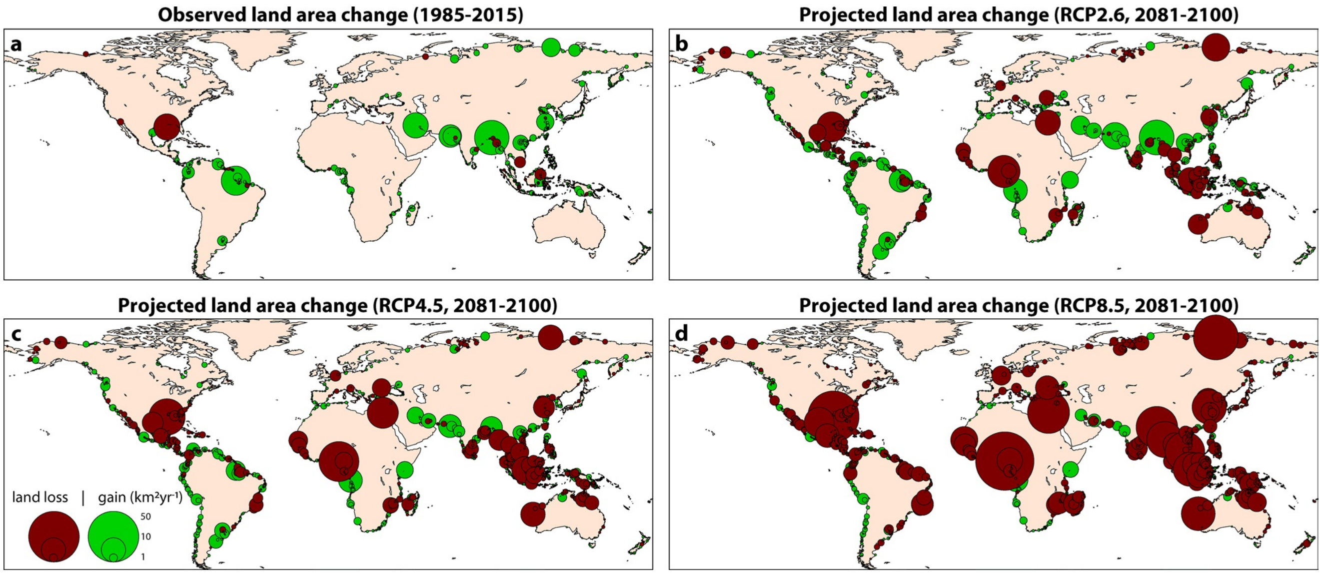

Figure 4. Spatial variability of delta land-area change, based on (a) observations and (b, c, d) projections of relative sea-level rise (RSLR) under representative concentration pathway 2.6, 4.5, and 8.5. Contribution of coastal subsidence to RSLR is included in the land area change projections.

Arctic deltas experience, on average, less RSLR because of ongoing glacial isostatic adjustment and gravitational effects. Land losses are projected to be larger, under all RCP scenarios, because they receive less sediment relative to their surface area. However, Arctic deltas will also experience many other effects of climate change that are not captured in our morphodynamic model (Barnhart et al., 2016; Lauzon et al., 2019). In general, our projections for individual deltas are highly uncertain and should be interpreted with caution (Thieler et al., 2000).

2.3. Drivers of Future Delta Land Area Change

We also assess the relative importance of various drivers of delta change. First, model results of an uninhibited growth scenario, without sea-level rise, river damming, deforestation, or subsidence, suggest a global gain about 758 km^2 yr^{-1} (Figure 5a). This rate is higher than what would be expected for long-term delta growth: modern total delta area (~900.000 km^2) divided by the age of modern delta initiation (~7,000 years) (Stanley & Warne, 1994) suggests a long-term average delta land area gain of about 130 km^2 yr^{-1}.

Modern observed delta land gain of 196 km^2 yr^{-1} is substantially lower than the uninhibited delta growth case (Figure 5a). We distinguish four drivers affecting delta growth: dams, deforestation, subsidence, and SLR, and compute expected delta area change if only one of these drivers were present. Model results suggests that, of those four drivers, sea-level rise has dominated the observed reduction in delta land gain from 1985–2015 compared to uninhibited conditions (Figure 5a). Note however that our assessment only includes fluvial suspended sediment load and not bedload, which adds to the total fluvial sediment load and responds differently to river dams (Kondolf, 1997; Nittrouer & Viparelli, 2014).

Climate-change driven sea-level rise is expected to continue to dominate river delta land loss. By the end of the century, sea-level rise under all RCP scenarios will greatly exceed other global drivers of delta land loss (Figure 5b).

2.4. RSLR Control on Delta Morphology

Besides a reduction of delta area, RSLR also affects delta plan-view morphology through its influence on the partitioning of fluvial sediment between delta topset, foreset, and bottomset (Blum & Törnqvist, 2000; Jerolmack, 2009; Kim et al., 2009). RSLR increases accommodation space and sediment deposition on the delta plain and lowers sediment delivery to the river mouth (Kim et al., 2009), which can make a delta more wave- or tide-dominated (Nienhuis et al., 2020).

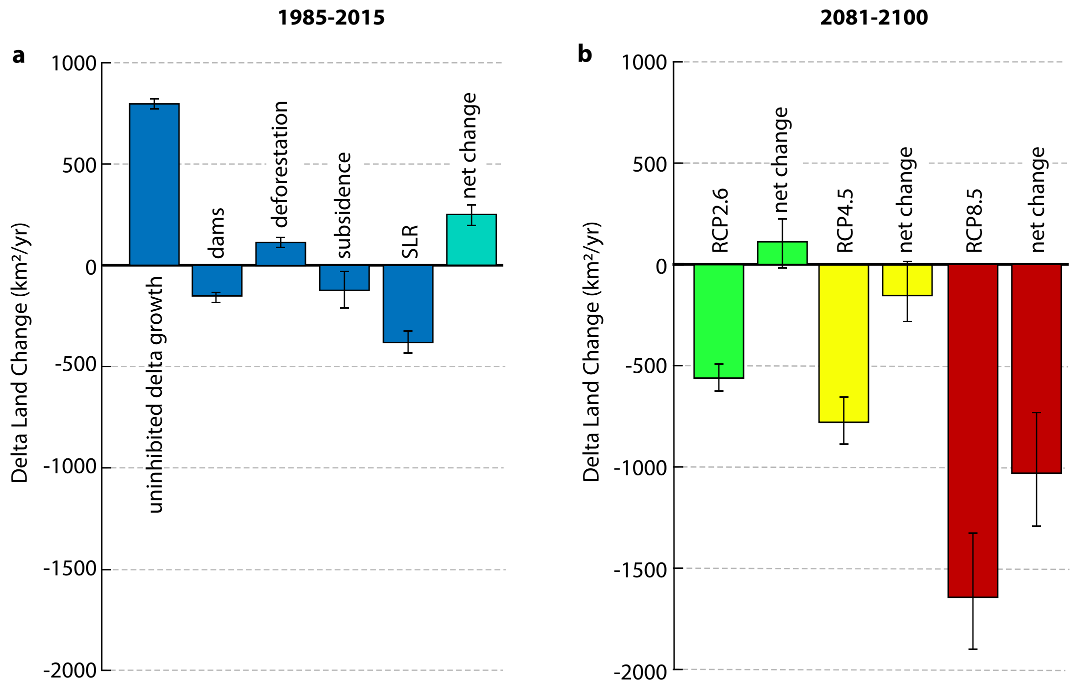

Figure 5. Relative influence of human drivers on delta change. Effect of different drivers of sediment supply or relative sea-level rise on delta growth, resulting in (a) net observed land gain from 1985–2015, and (b) projections of future delta change if the influence of dams, deforestation, and subsidence remain the same.

Our model suggests that for a global mean RSLR of 10 mm yr^{-1}, the rate of delta plain accommodation space creation is equivalent to about 80% of the global fluvial sediment flux (Figure 6a). Such a RSLR rate would leave 20% of the fluvial sediment supply available at the river mouth for redistribution along present-day coasts. RSLR and delta response to RSLR varies between deltas: following our model predictions for RCP8.5 by 2100, we predict that 20% of all coastal deltas will be in forced retreat (abandoned of all fluvial sediment

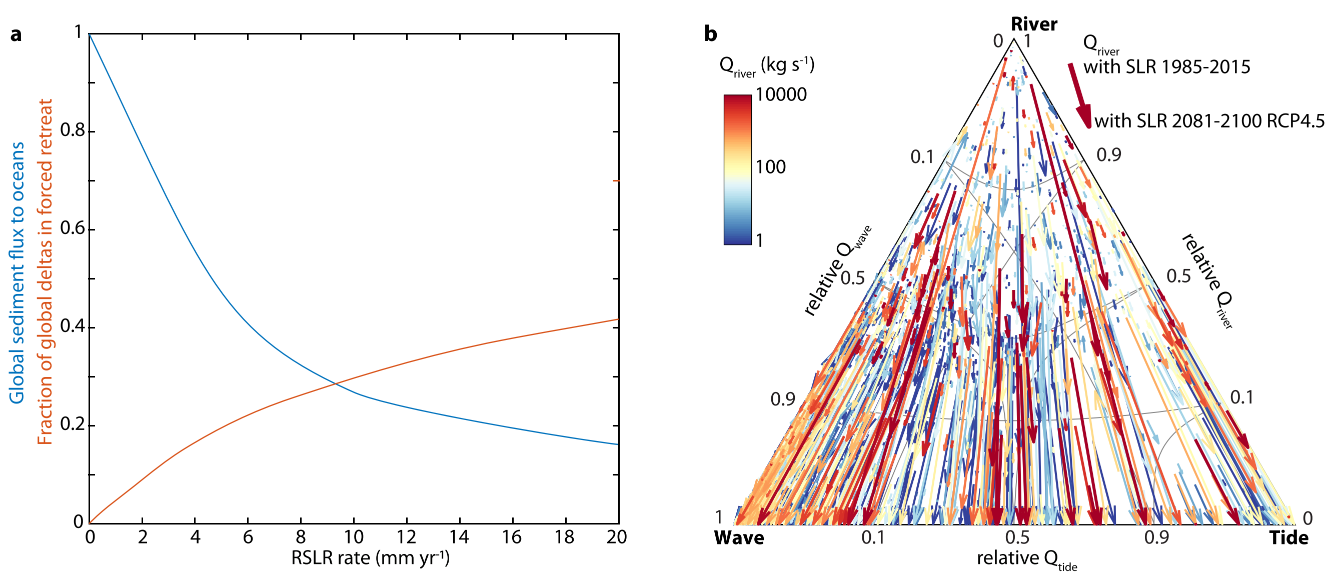

Figure 6. Effect of relative sea-level rise (RSLR) on delta morphology. (a) Effect of RSLR on (in blue) the global fluvial sediment flux to deltaic river mouths and (in red) the fraction of all coastal deltas (n = 6,402) where the river mouth is abandoned, and no fluvial sediment reaches the river mouth. (b) Effect of the reduced sediment flux to the river mouth on delta morphology, comparing modern sea-level rise (SLR) to SLR under representative concentration pathway4.5 by 2100. Ternary diagram indicates relative influence of wave-, tidal- and fluvial sediment flux on delta morphology (Nienhuis et al., 2020).

supply at the river mouth). RSLR rates from 1985–2015 have trapped 20% of the global fluvial sediment supply onto the delta plain, in addition to delta sediment trapping that results from delta progradation. This will increase to 60% by 2100 if emissions follow RCP8.5, a high-end scenario. The slope of the sediment flux curve (in blue) exceeds the slope of the fraction of deltas curve (in red), indicating that large deltas are more strongly affected by RSLR (Figure 6a).

Using a new model for river delta morphology (Nienhuis et al., 2020), we can investigate potential plan-view effects of RSLR-induced sediment trapping on the delta plain (Figure 6b). A decrease in fluvial sediment supply that arrives at the river mouth results in a shift in the river mouth sediment balance toward tidal and wave-driven sediment flows. Following our model simulations for RCP8.5 by 2100, we predict that 10% of all river-dominated deltas will transform to wave-or tide-dominated deltas, although it does not specify a rate of change for delta morphology.

3. Discussion and Conclusions

Our simplified delta area change model captures broad global patterns and can be tested against global observations. Accurate predictions for individual deltas remain challenging. Human-landscape interactions, most notably the construction of flood protection defenses, have had, and will have, a significant effect on delta sedimentation and their (short-term) response to RSLR. Human-landscape interactions also challenge the accurate observations of delta morphodynamics (Besset et al., 2019). Prediction accuracy is limited because of uncertainties in estimates of subsidence rates over time, sea-level change, fluvial sediment flux, and present-day morphology. Fluvial sediment supply and subsidence rates are unlikely to remain the same into the future. River damming is projected to overtake deforestation to further reduce fluvial sediment supply to deltas (Dunn et al., 2019). Population pressure and associated groundwater withdrawal will likely increase subsidence rates in many densely populated deltas (Herrera-García et al., 2021; Keogh & Törnqvist, 2019). At the same time adaptation measures may reduce subsidence rates in areas which are already under pressure.

Other uncertainties stem from model assumptions. We assume a linear delta response to RSLR and sediment supply. Such a response may be justified for predictions on short timescales (~100 years) relative to the age of river deltas (~7,500 years) (Lorenzo-Trueba et al., 2009). On the other hand, we also assume that delta morphodynamics can be expressed by a morpho-kinematic mass balance approach–an assumption that typically only holds for long timescales or for small deltas. On short timescales, land area change from individual coastal and river floods (Ward et al., 2020) or autogenic (free) delta morphodynamics such as avulsions or channel migration would likely obscure allogenic (forced) change (Li et al., 2016) of an individual delta. Future model projections should aim to be more spatially explicit, such as those by Vousdoukas et al. (2020), and indicate where within deltas land area change is likely to occur.

Our uncertainty assessment combines data and model errors and shows that our predictions are relatively robust when applied on a global scale. Additionally, our methods and data presented here provide quantitative and morphodynamic projections that offer an improvement over frequently used bath-tub models and agree with historic data on delta land area change. Together with studies such as those by Bamunawala et al. (2020), who apply similar methods to tidal inlets, it shows the potential use of simplified, morphodynamic models for the characterization of future coastal change.

Our predictions show substantial risk of land loss from climate-change driven RSLR. We estimate that RSLR under RCP8.5 (a high-end scenario, Hausfather & Peters, 2020), will lead to the disappearance of about 37,178 ± 17,919 km^2 of deltaic land–equal to about 5% of total delta area. Delta top sedimentation can also lead to widespread wave and tidal reworking of deltas. There are also other risks to deltas driven by RSLR that are not included in this study, such as increased coastal flooding, salinity intrusion, and river flooding.

Many RSLR-driven risks to river deltas, including the land loss discussed in this study, can be reduced with appropriate management strategies that support efficient use of the available sediment. Delta plain sedimentation strategies such as river diversions are a good example (Paola et al., 2011). Our results highlight that these approaches can protect deltas against some of the consequences of climate-change driven RSLR and should be encouraged.

Data Availability Statement

Model code and data to reproduce the findings and figures are available via OSF (doi:10.17605/OSF.IO/R4U8K).

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