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REPLY

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INTRODUCTION

To a large extent, geology is a science of solving inverse problems based on some data and scientific principles. Solutions to these types of problems are not unique, especially when using different data, invoking different principles, or both. It is not surprising that the discussant and we have reached different conclusions on the same specific issue of land loss along the coast of Louisiana because we use different observations and view those observations in a different context. The objective of this reply is to orient the reader, who then can decide which approach is more likely to be the correct analysis.

OUR MODEL

We believe that the problem is more complex than stated by the discussant. In our view, the following factors cannot be disregarded in explaining land losses in Louisiana: (1) land subsidence, (2) engineering across the entire Mississippi basin, (3) evolving geology of bird-foot deltas, (4) canal constructions, and (5) sea-level rise. We regard the following as relevant and valid among the data: (1) time series of wetland extent from 1932 to 2011, prepared by the U.S. Geological Survey (Couvillion *et al.*, 2011) and reproduced as Figure 1 in our paper (Olea and Coleman, 2014); (2) geodetic measurements of subsidence by Shinkle and Dokka (2004); and (3) past fluctuations in sea level published by various authors, in particular the fourth report by the Intergovernmental Panel on Climate Change (Bindoff *et al.*, 2007), recently updated by Rhein *et al.* (2013).

According to the geodetic surveys of Shinkle and Dokka (2004), the entire delta and the lower portion of the Mississippi River valley in Louisiana are experiencing a regional subsidence at an average rate of 10 mm/y. We have confirmed claims by various authors that this subsidence is the result of three main geologic processes that have been acting in the region from millennia to millions of years: (1) accommodation of the lithosphere to the weight of accumulated sediments going back to the Triassic (Ivins, Dokka, and Blom, 2007), (2) normal faults contributing to the displacement of the sediments southward toward the basin center (Gagliano, 2005), and (3) compaction of sediments inversely proportional to age (Meckel, ten Brink, and Williams, 2006). The implication of the magnitude and nature of these processes is that sediments in southern Louisiana have been subsiding for at least several centuries at an average rate of about 1 m per century.

Surface sediments in southern Louisiana are mostly Holocene in age (Louisiana Geological Survey, 2010), which implies that in recent geologic history the coast has been accreting. Considering the areal extension of the sediments, the wetlands were expanding at an average rate of 3.2 km^2/y because of an average sediment supply estimated at 240–300 million metric tons per year (Blum and Roberts, 2009; Working Group for Post-Hurricane Planning for the Louisiana Coast, 2006). This build-up is also an argument to reject net land losses by erosion and hurricanes during precolonial times; deltas are dynamic systems in which avulsion is part of a natural evolution, and erosion is overcompensated by new sedimentation (Blum and Roberts, 2012). In the more recent centuries, the Mississippi delta has been denied a normal evolution in two stages. First, there was a gradual construction of levees that prevented sediments from freely dispersing, thus denying sedimentary compensation of subsidence for that part of the delta above sea level and nutrients for the healthy growth of vegetation, forcing the sediments to discharge instead mostly beyond the delta plain onto the submerged continental platform. Second, thousands of dams are silting artificial lakes, preventing sediments from reaching the delta. The current result is a starving delta receiving lower volumes of sediments, which in the past were sufficient to build up all of southern Louisiana (Alexander, Wilson, and Green, 2012). The problem has been exacerbated by a modern sea-level rise, which in the last 80 years has been recorded to account for 14 cm (*e.g.*, Bindoff *et al.*, 2007), amounting to 17.5% of the land subsidence.

Canal constructions may be regarded as a third form of disruption of the Mississippi delta. Amounting to an accumulated length of approximately 17,000 km (Bjerstedt, 2011),

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canals are certainly features that do not contribute to preserving a delta. Considering that Louisiana canals are on average 21.3 m wide when constructed (Lopez, 2003), direct digging of the wetlands has reduced their areal extension by 360 km^2 or 2.5% of the present area of the wetlands in Louisiana (Day *et al*., 2005). Different authors have reported vastly different numbers in terms of additional indirect loss area by subsequent erosion and alteration of the hydraulic conditions. There is agreement, however, that canal constructions peaked in the 1970s, coinciding with a boom in drilling and production by oil companies. Rates of land loss reported by the U.S. Geological Survey (Couvillion *et al*., 2011) do show an acceleration in land loss during a period from 1974–88, accounting for as much as an additional 1000 km^2 land loss over the historical rate of about 50 km^2/y before and after this period. This surge represents a 60% increase in land loss relative to the trend before and after 1974–88, which may be attributed primarily to canal constructions. An area of 1000 km^2 is almost three times the original surface of the canals just after construction.

Even if the entire 1000 km^2 land loss anomaly in the data of Couvillion *et al*. (2011) is attributed to canal construction, this amount accounts only for 20.4% of the 4900 km^2 total land loss. Conversion of the combined effect of land surface drop and sea-level rise into inundation is difficult because of a lack of adequate data to develop an accurate model, such as high resolution topographic maps for 1932, the start of the period of analysis. Given the sediment starvation and the topography of the Louisiana wetlands, however, a land surface drop of 94 cm below the present sea level at the very least should account for the balance of the 3900 km^2, a 79.6% of total land losses.

Looking into the future, the average subsidence is expected to continue unaltered at least for several centuries, assuring continuation of land loss despite mitigation efforts (Couvillion *et al*., 2013). Adverse effect of canal constructions may even reverse if efforts to force oil companies to backfill canals prosper (Fisher, 2013). Unfortunately, there is an impending possibility that sea-level rise will accelerate (Lynch, 2014; Rhein *et al*., 2013), in which case any possible slowing in land loss will be reversed. If sediment starvation is not addressed (Paola *et al*., 2011), with or without backfilling or acceleration of sea-level rise, subsidence by itself eventually will bring to open waters additional wetlands (Dokka, 2006; Kim *et al*., 2009), losses that will occur even if the canals never would have been dug. This is far from being a rosy scenario.

THE DISCUSSANT'S MODEL

If correct solutions to inverse modeling problems using good data are difficult, working with inaccurate or incomplete information makes achieving an adequate solution even more challenging. The discussant uses as primary evidence a dataset for the period 1932–90 prepared from 15-minute base maps by Britsch and Dunbar (1993). In addition to ignoring 24 years of the most recent history, the data were already proved 14 years ago to be inadequately collected (Day *et al*., 2000) because (1) aggregating the losses at the level of 15-minute quadrangle maps is too broad of a resolution and (2) the analysis was biased by eliminating cells containing less than 15% of land.

The discussant is bringing back into discussion, as Figure 3, a scatterplot originally published by him in 1997 (Turner, 1997) that used data from the study by Britsch and Dunbar (1993) and is repeating a series of arguments already dismissed by others (*e.g*., Gosselink, 2001; Priest and Theriot, 2009). At the core of the discussant's modeling now and in 1997 is the finding that regression lines of land loss on canal density go through the origin, which is subsequently used to postulate that when there are no canals there is no land loss. Using more properly collected data, Day *et al*. (2000) have shown that Turner's results are an artifact of the modeling; their direct losses show no correlation with other losses for the entire dataset, and regression lines do not go through the origin when subdividing the data by regions.

To defend results that the discussant is still supporting, he denies what is commonly known about the geology of bird-foot deltas by claiming that salinity does not have any negative effect on the vegetation, subsidence is irrelevant, construction of levees has nothing to do with wetland loss, and sediment starvation is a myth. We believe that all these facts are so well documented in the geological literature (*e.g*., Blum *et al*., 2008; Coleman, Roberts, and Stone, 1998; Day and Giosan, 2008; Nyman, 2014; Yuill, Lavoie, and Reed, 2009) that they are not worth refuting, except perhaps for the last claim. Considering that the discussant gives several references to prove the point that sediment supply is back to normal after going to an anomalous high level from the beginning of the European colonization to 1950, we feel it necessary to mention calculations to the contrary by Blum and Roberts (2009). In their Figure 2, reproduced as Figure 11 in our paper, Blum and Roberts show that the current sediment load of the Mississippi River is not only below the 1950 level but also below the supply necessary to build up the Louisiana coast during the Holocene.

In summary, several good datasets allowed us to conduct an inverse modeling honoring more geologic principles than the results supported by the discussant based on one deficient sampling.

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