LAND-USE CHANGE AND TIDAL CREEK SEDIMENTATION IN COASTAL WATERSHEDS OF NORTH CAROLINA

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ABSTRACT

Charles Dawson Deaton: Land-use change and tidal creek sedimentation in coastal watersheds of North Carolina
(Under the direction of Antonio B. Rodriguez)

Terrestrial landscape alterations cause changes along the coast, where rivers deliver sediments to estuaries and oceans. In contrast to major rivers, tidal creek watersheds are small, but they are numerous and drain much of the eastern United States' coastal-estuarine land area. Coastal watersheds are frequently hotspots of development, and in North Carolina, residents have expressed concerns about creeks infilling, becoming unnavigable for boaters and uninhabitable for fish. To understand the relationship between land-use change and creek infilling, sedimentation rates calculated from ^{210}Pb in cores from twelve tidal creeks across North Carolina were compared to changes in watershed land use 1959-2010. Results indicate that land-use change, particularly increasing non-agricultural development, has the potential to drive infilling of tidal creeks, although hydrological conditions impose some limits and are responsible for the partitioning of increased sediment loads between deposition in creeks and export to larger estuaries.

ACKNOWLEDGEMENTS

Many thanks to Tony, Brent, and Joel for their feedback and assistance throughout this project, and to Molly Bost and Rich Mahoney for their continuous assistance in the field and lab, without which this project would not have been possible. I would also like to thank Anna Atencio, Carson Miller, Naomi Becker, Ivonne Guzman, Rachel Quindlen, Jill Arriola, and Alex Smith for providing help throughout the project with various tasks in the field and lab.

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LIST OF ABBREVIATIONS

CCAP	Coastal Change Analysis Program
CFCS	Constant Flux-Constant Sedimentation
CRS	Constant Rate of Supply
MAR	Mass Accumulation Rate
NC	North Carolina
RSLR	Relative Sea-Level Rise
SAR	Sediment Accumulation Rate

CHAPTER 1: LAND-USE CHANGE AND TIDAL CREEK SEDIMENTATION IN COASTAL WATERSHEDS OF NORTH CAROLINA

Introduction

Tidal creeks are common features along the estuarine shorelines of the US Atlantic and Gulf coasts. The term “tidal creek” has previously been used to describe a wide range of systems, including wetland channels and tidal freshwater tributary creeks (Mallin and Lewitus, 2004). For this study, we define tidal creeks as systems which perennially drain low-gradient coastal watersheds that are typically between 1 and 50 km^2, are tidal their entire length, and discharge into larger estuaries or lagoons. Typically, tidal creeks are composed of an upper reach, in which the narrow main channel is constricted by salt marshes, and an open-water lower reach, characterized by fringing and island marshes, oyster reefs, tidal flats, and/or seagrass beds. Tidal creeks are distinguishable from wetland channels (which lack a terrestrial watershed), coastal lagoons (which have direct connection to the ocean and lack a fluvial morphology), and drowned river-mouth estuaries (which have large watersheds and extensive non-tidal freshwater reaches).

Tidal creeks can contain a number of important habitats, including marshes, oyster reefs, seagrass beds, tidal flats, and subtidal bare sediment. These ecosystems provide valuable services, such as nursery habitat for fishes, carbon sequestration, erosion control, and protection from storm damage (Barbier et al. 2011, Grabowski et al. 2012). Tidal creeks function similarly to the larger downstream estuaries into which they merge, and because of their small size and location at the gateway of the terrestrial-marine transition, they may serve as contaminant filters and sentinels of change for larger estuarine environments.

In the centuries following European settlement of North America in the early 18th century, tidal creeks have experienced changes in geometry and hydrology, including channel dredging, infilling and ditching of wetlands, and construction of beam bridges. Additionally, watershed modifications such as agricultural ditching and urban stormwater drainage have altered natural watershed boundaries. In some cases, watershed modifications allow interbasin transfers during high-water events. As with most of the lower Atlantic coastal plain, these watersheds were historically dominated by upland forests and palustrine wetlands (Henry et al. 1995), but today coastal watersheds sustain a wide range of human land uses, including agriculture, silviculture, and residential/commercial development. Development especially has expanded following the rapid increase in population of coastal-shoreline counties across the US, which added 125 persons per square mile between 1970 and 2010. In 2010 the population density in coastal-shoreline counties was 446 persons per square mile, compared to only 105 persons per square mile for the US as a whole (NOAA National Ocean Service, 2013).

Land-use modification has been demonstrated to have impacts on sedimentation regimes in larger watersheds and estuarine systems. Previous work established relationships between forest-clearing and increased sediment delivery in larger estuaries, such as Plum Island Estuary, MA (Kirwan et al. 2011) and the Newport River Estuary, NC (Mattheus et al. 2009). Changes in sediment delivery can have disproportionately large effects, causing estuarine habitat transitions, such as between tidal flats and marshes (e.g. Kirwan et al. 2011; Gunnell et al. 2013; Couvillion et al. 2017), or seagrass beds and bare sediment (e.g. Carr et al. 2010). Such habitat transitions alter the ecological services and impact the human usability of estuarine ecosystems, making sedimentation a concern for managers.

While relationships between land-use change and sedimentation are well established in larger watersheds, relatively little attention has been devoted to understanding sedimentation in smaller coastal watersheds. In eastern North Carolina, most tidal creeks are designated as Primary and/or Secondary Nursery Areas (PNA/SNA) by the North Carolina Division of Marine

Fisheries (NCDMF), placing restrictions on fishing, including banning trawl nets, long haul seines, swipe nets, and dredges, to protect juvenile fishes using the creeks as nursery habitat (NCAC 2007). Further, NCDMF designated sedimentation as one of its four priority habitat issues, specifically noting a need to understand the impacts of sedimentation on the function of PNAs, including tidal creeks (NCDEQ, 2016). Previous studies have documented the impacts of coastal watershed land-use change on fish abundance (Meyer 2011) and water column quality in tidal creeks (e.g. Mallin et al. 2000, Ensign and Mallin 2001, Sanger et al. 2013), but did not address benthic sedimentation. Darrow et al. (2017) made estimates of sedimentation rates in tidal creeks in Grand Bay, MS/AL, but did not investigate changes in sedimentation, and did not attempt to link those rates to land use. Corbett et al. (2017) determined sedimentation rates in three tidal creeks in eastern NC (including Oyster Creek, one of this study's sites) and noted changes in sedimentation rates in some cores but did not have long-term quantitative land-use change data to compare to their observed changes in sedimentation rates. Corbett et al. (2017) did note that sedimentation rates in their sites generally outpaced the local rate of relative sea-level rise (RSLR), indicating creek infilling, albeit at a rate likely too slow to be noticeable by boaters, fishermen and landowners.

Here, we present a multi-decadal analysis of both land-use change and changes in sedimentation in tidal creeks. Using 12 coastal watersheds across a gradient of land-use in eastern North Carolina, we demonstrate that changes in land use can cause changes in sedimentation rates in the tidal creeks draining those watersheds, with increasing developed area in particular being linked to accelerating sedimentation. However, tidal hydrodynamics and watershed geometry may impose limits on the degree and timing of changes in creekbed sedimentation, determining whether land-use-induced changes in sediment supply are retained in the tidal creek basin or exported to downstream estuaries.

Study Area

We selected 12 creeks from across eastern North Carolina (Figure 1), representing a gradient of land use. Six creeks (Oyster, Tusk, Sleepy, Ward, Ware, and Gales) are located in Carteret County, and the other six (Futch, Pages, Howe, Bradley, Hewlett's, and Whiskey) are located in New Hanover County. Watersheds in Carteret County are generally more rural, with large proportions of agriculture and forest, while watersheds in New Hanover County are generally more urban and suburban, as most of them are in or adjacent to the city of Wilmington. The creeks near Wilmington have been previously included in studies of land-use change and water quality (e.g. Mallin et al. 2000, Sanger et al. 2013). The creeks included in this study represent 12 out of at least 40 creeks across the 150 km our study area spans. From south to north, local rates of RSLR increase from 2.27 +/- 0.35 mm yr^{-1} in Wilmington, NC, to 3.00 +/- 0.36 mm yr^{-1} at Beaufort, NC, and to 4.15 +/- 1.21 mm yr^{-1}, north of our study area at Oregon Inlet, NC (NOAA Tides and Currents stations 8658120, 8656483, and 8652587, respectively). Tidal range increases from northeast to southwest in our study area, from a great diurnal range (the difference of mean higher high water and mean lower low water) of 1.4 m at Wilmington to 1.1 m at Beaufort to 0.2 m at Oyster Creek (NOAA Tides and Currents stations 8658120, 8656483, and 8652437, respectively). The creeks in Carteret County drain from the Pamlico Terrace, except for Gales Creek, which drains across the Suffolk Scarp, which formed near the end of the last interglacial (77 ± 8.8 ka: Phillips, 1997). The creeks in New Hanover County drain across both the Suffolk Scarp, which delineates the mainland shoreline there, and the parallel Hanover scarp, just landward of the Suffolk Scarp (Zullo and Harris, 1979). Scarps represent former sea-level highstand shorelines, so watersheds spanning scarps are both sandier and higher-relief than watersheds entirely contained in the Pamlico terrace.

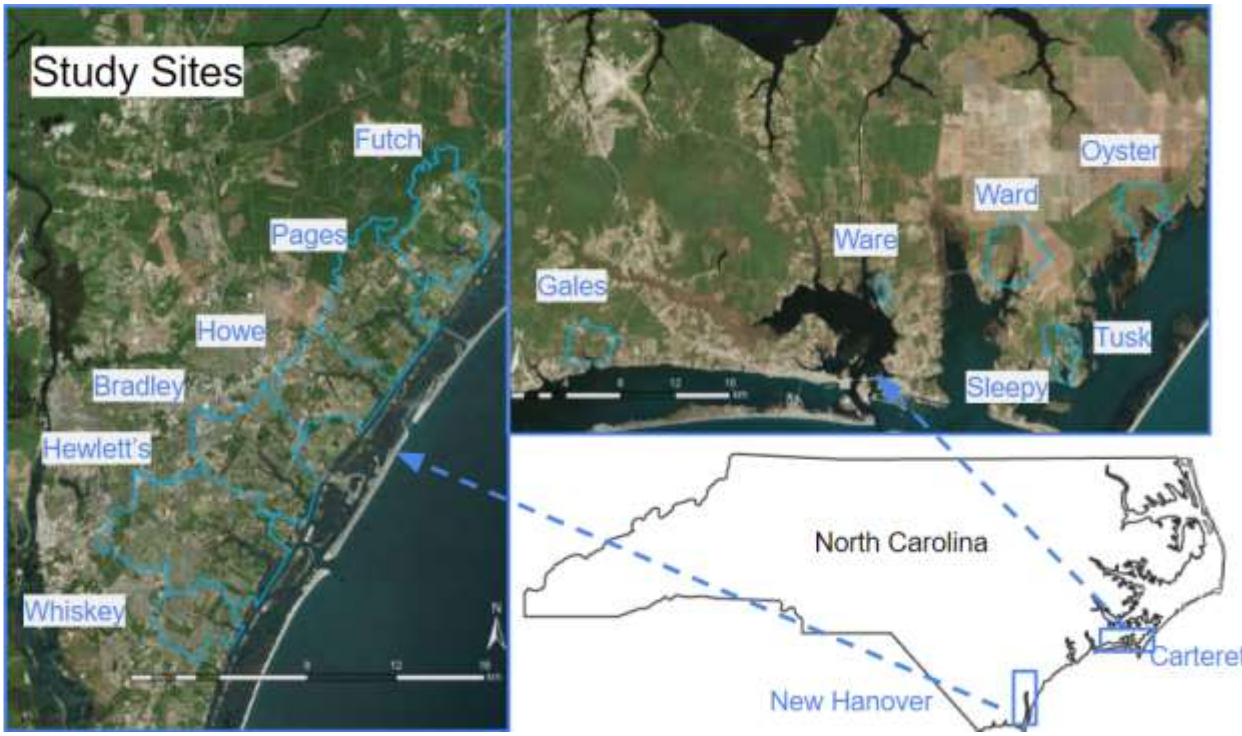


Figure 1. Site map. Tidal creek watersheds are outlined in blue over aerial imagery. Left: New Hanover County creeks. Upper right: Carteret County creeks. Bottom right: location of New Hanover and Carteret Counties within North Carolina.

Methods

Coring and analysis

Cores were collected in each creek where channels widened at the transition between the upper and lower reaches. This location was chosen with the expectation that sediments sourced from the watershed would settle onto the creekbed at a higher rate than landward and seaward locations in response to increased flow divergence and a drop in flow velocity as the channel abruptly widens. Therefore, we would expect that these cores would represent maximum long-term sedimentation rates in the creekbeds. Corbett et al. (2017) took three cores along the central axis of nearby tidal creeks and noted that sedimentation rates were lowest near where our cores were taken and generally higher in the two more seaward cores, indicating maximum sedimentation rates within these creeks may exceed reported rates and/or the existence of downstream sediment sources. Cores were 10.16 cm in diameter, collected in the summer of 2016, and extruded in 1-cm sections. As in Croswell et al. (2017), each section was freeze-dried, crushed, split into fine and coarse components using a 63-micron sieve, and weighed. The fine components of each section were subsampled, and ^{210}Pb was determined via isotope-dilution alpha spectrometry, measured by the granddaughter isotope ^{210}Po, which occurs in secular equilibrium with ^{210}Pb.

^{210}Pb is a radioactive isotope in the ^{238}U decay series with a half-life of 22.3 years. When measured by alpha spectrometry, it is detectable to 5-6 half-lives, or approximately 120 years, making it an ideal tracer for multi-decadal timescales. ^{210}Pb is produced in the atmosphere and in situ by decay of ^{222}Rn, and atmospheric ^{210}Pb is removed by rainfall and introduced to land or water, where it readily adsorbs to sediments. Sediment burial cuts off the atmospheric source, and buried concentrations decay exponentially toward the concentration supported by in-situ production. Thus, using the known half-life, the age of buried sediments can be determined by fitting an exponential curve to measured excess ^{210}Pb concentrations over depth (Goldberg 1963).

Sedimentation rates were constructed from excess ^{210}Pb concentrations for all creeks using a Constant Flux-Constant Sedimentation (CFCS), and a Constant Rate of Supply (CRS) model where appropriate. The CFCS model provides a single sedimentation rate for the entire core or a discrete subsection, and the CRS model is used to determine changes in sedimentation rate at each sampling interval (Sanchez-Cabeza and Ruiz-Fernández, 2012).

Land use classification

Watersheds for the creeks in Carteret County were delineated by hand in ESRI ArcGIS using digital elevation models (DEMs) from lidar collected in 2014 (NOAA OCM, 2014). Watersheds for creeks in New Hanover County were obtained from the New Hanover County Open Geospatial Data portal (New Hanover County, 2015). Watershed slope was calculated using the Slope tool in the Surface toolbox in ESRI ArcGIS, and watershed relief was calculated as the difference in the highest and lowest 10% of elevation points in the DEMs. Land-use change from 1959 to 1993 was hand-digitized in ESRI ArcGIS from georeferenced aerial imagery from the USGS Aerial Photo Single Frames records collection and National High Altitude Photography (NHAP) program. Land-use was classified as one of forest, cleared forest, agriculture, developed, or water/intertidal. Land-use change from 1996-2010 was obtained from the Coastal Change Analysis Program (CCAP: NOAA, 2016) and reclassified to match the same categories used for the 1959-1993 imagery (reclassification table provided in Appendix A). The earliest reclassified CCAP data displayed little difference from the immediately preceding manually-digitized land-use classes, and in instances where there was an apparent significant (>5%) change in land use from 1993 to 1996, aerial photographs from 1993 and 1996 were compared to ensure that the change did in fact occur. No major deviations were noted in comparisons, indicating that these two datasets are indeed comparable.

Results and interpretations

^{210}Pb-derived sedimentation rates

Where possible, sedimentation rates were determined using both a CFCS model (Figure 2), which provides a single, long-term averaged sedimentation rate, and a CRS model, which is well-suited for resolving changes in rates among samples. The CRS model was applied to eight of the twelve creek cores where enough of the inventory was measured to approximate the full ^{210}Pb inventory by extrapolation. The whole-core CFCS model was applied to cores from ten of the twelve creeks, and a two-segment CFCS model was applied to six cores (Table 1) where the log-excess ^{210}Pb vs. depth profile appeared to show a significant break in slope. CFCS-modelled rates vary by an order of magnitude among creeks, but variations do not cluster geographically.

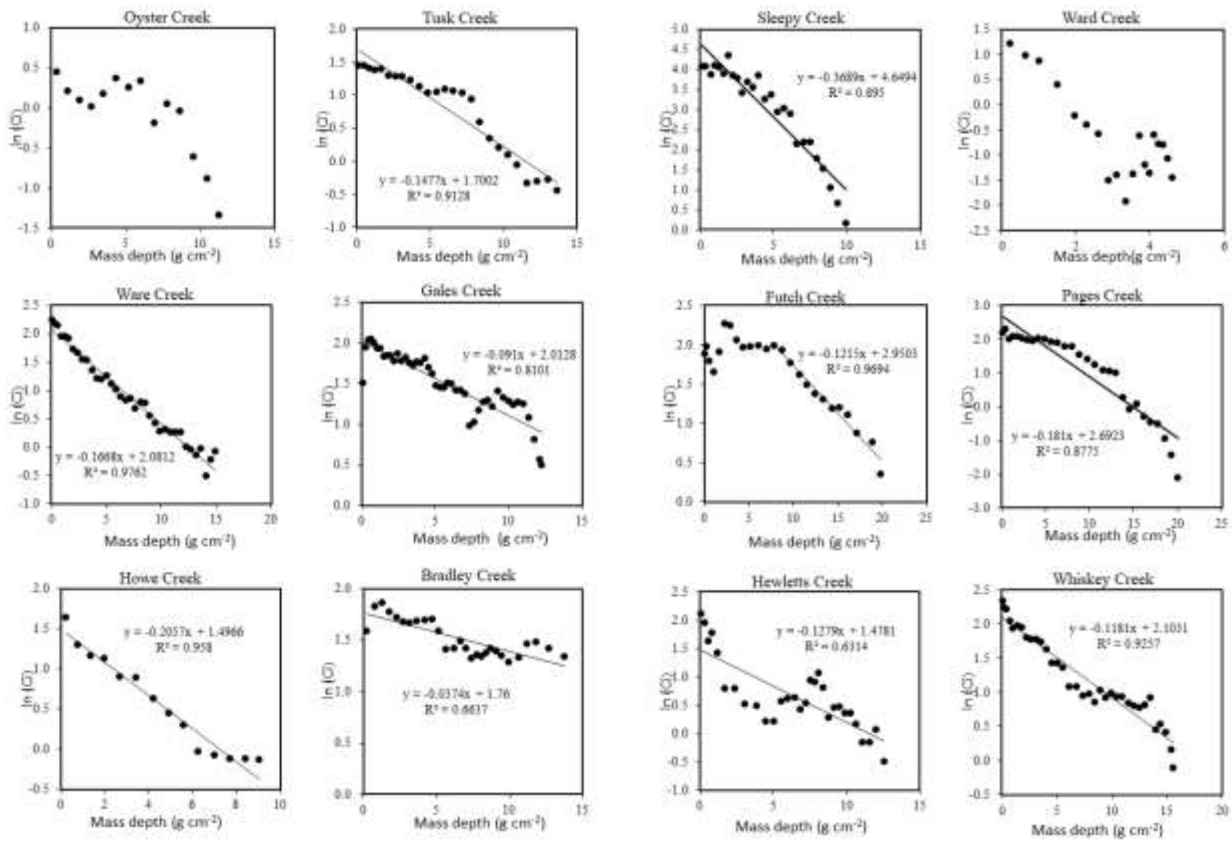


Figure 2. Log-excess ^{210}Pb vs. mass depth profiles for each creek. For all creeks except Oyster and Ward, the fit of the whole-core CFCS model is also plotted; sedimentation rates calculated from the CFCS model are presented in Table 1. Creeks are arranged left to right, geographically from northeast to southwest along the coast

Creek Name	Whole-Core CFCS MAR (g cm^{-2} yr^{-1})	Whole-Core CFCS SAR (cm yr^{-1})	Upper CFCS MAR (g cm^{-2} yr^{-1})	Lower CFCS MAR (g cm^{-2} yr^{-1})	Upper CFCS SAR (cm yr^{-1})	Lower CFCS SAR (cm yr^{-1})	Break Year
Tusk	0.21	0.37	0.45	0.16	0.90	0.25	1998.9
Sleepy	0.08	0.20	0.15	0.05	0.44	0.10	1975.8
Ware	0.19	0.43	--	--	--	--	--
Gales	0.34	1.23	0.33	0.11	1.27	0.31	1989.0
Futch	0.26	0.28	--	--	--	--	--
Pages	0.17	0.23	0.35	0.09	0.50	0.12	1977.1
Howe	0.15	0.22	--	--	--	--	--
Bradley	0.83	1.80	--	--	--	--	--
Hewletts	0.24	0.57	0.08	0.21	0.15	0.59	1942.6
Whiskey	0.26	0.53	0.19	0.36	0.47	0.70	1985.8

Table 1. Sedimentation rates by creek, arranged geographically from northeast to southwest along the coast. Mass accumulation rates (MAR) and sediment accumulation rates (SAR) as determined by the whole-core CFCS model, and by the two-segment CFCS model where appropriate. The 'Break Year' column indicates the year at which the lower (older) CFCS rate ended and the upper (more recent) CFCS rate began. '--' indicates that the two-segment CFCS model was deemed inappropriate for that core.

Sedimentation rates in Futch and Bradley Creeks were only described using a CFCS model. Bradley Creek's consistently high sedimentation rate of 1.8 cm yr^{-1} extended too deep in the core to analyze enough samples to capture the full excess ^{210}Pb inventory. The scattered excess ^{210}Pb concentrations from 0 to 7 cm and homogeneity from 7 to 12 cm in the Futch Creek core represent one or both of a relatively deep mixing zone or a single mass-deposition event, either of which would create a misleading profile using the CRS model. The CFCS model provides a rate of 0.28 cm yr^{-1} for Futch Creek, excluding the upper 12 cm, and a rate of 1.8 cm yr^{-1} for Bradley Creek.

In the Ward creek core, the total recovered inventory (approximately 0.2 dpm cm^{-2} yr^{-1}) was less than one fourth of what was expected based on atmospheric deposition alone (0.8 dpm cm^{-2} yr^{-1}: Benninger and Wells, 1993), indicating significant erosion of the creekbed sediments. Below 10 cm, dry bulk density was low (0.1-0.2 g cm^{-3}) and grassy debris was observed in the core, which we interpret as the remains of a seagrass bed. This indicates that the creek was once vegetated and likely became net-erosional after the loss of vegetation. While this may have been linked to land-use change, such as agricultural runoff contributing to eutrophication (Kemp et al. 2005) or initial European deforestation and "cut-out-and-get-out" forestry through the 1930s (Phillips, 1997), the lack of a complete ^{210}Pb inventory precludes establishing a definitive temporal relationship. As the watershed with the most total agricultural area and one of only two (along with Ware) with a large proportion of agricultural area (Figure 3), the lack of sedimentation rates from this core prevents us from drawing conclusions about the impacts of agriculture in tidal creek watersheds.

Similar to Ward Creek, the total recovered inventory from Oyster Creek (approximately 0.4 dpm cm^{-2} yr^{-1}) was less than one half of what was expected based on atmospheric deposition alone (0.8 dpm cm^{-2} yr^{-1}), indicating significant erosion of the creekbed sediments in this core also. Data from three cores in Oyster Creek, as reported by Corbett et al. (2017), present total ^{210}Pb inventories in line with expected inventories, further supporting that sedimentation rates obtained from our core would not be representative of Oyster Creek. Accordingly, Ward and Oyster Creeks have been removed from all analyses.

Among the remaining creeks, both the CFCS (Table 1) and CRS models (Figure 4) agree that Tusk, Sleepy, Gales, and Pages experienced an increase in sedimentation rate through time. The CFCS model for Hewletts and Whiskey indicates a decrease in sedimentation rate, while the CRS model indicates an increase followed by a decrease for both cores (changing in the mid-1990s and mid-1980s, respectively: Figure 4g-h). Given that the two-segment CFCS model, as presented here, only provides for one change in sedimentation rate, it is likely that the change is weighted by the upper (more recent) sections of the core, and that the increase-then-decrease pattern suggested by the CRS model is accurate. Ware and Howe, which did not vary enough on excess ^{210}Pb-depth plots to warrant using a two-segment CFCS model, display minor variation but no major changes in CRS-modelled sedimentation rate.

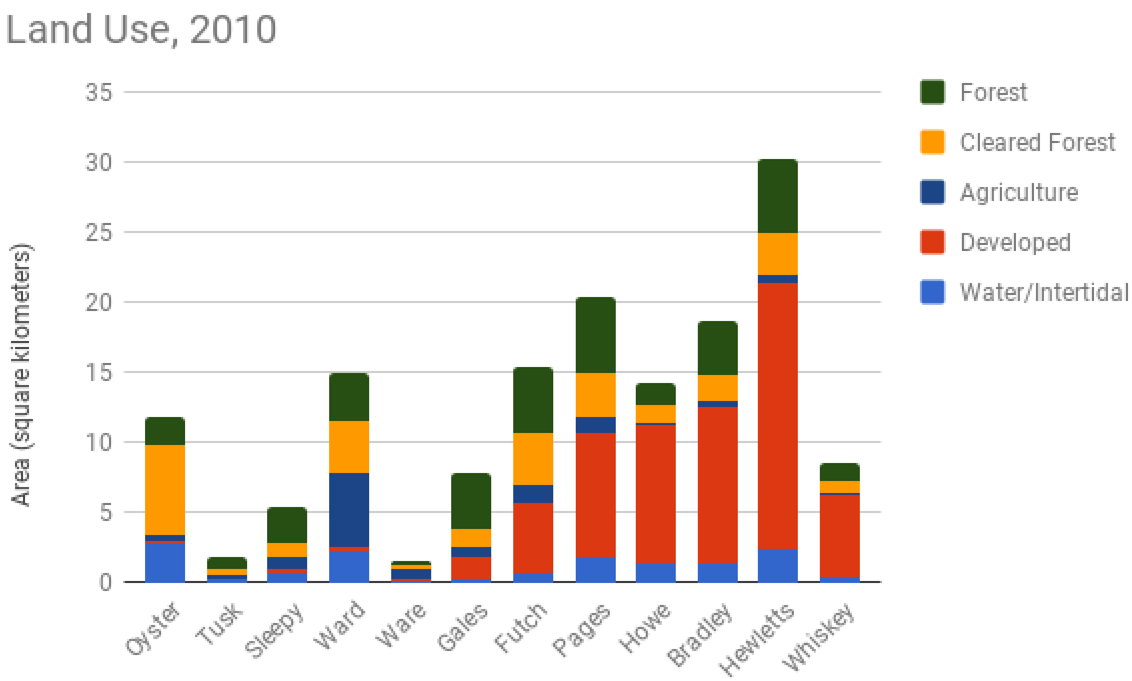
In sedimentation rates obtained from the CRS model, the upper sections of most cores appear to show a rapid increase in SAR but a constant or decreasing MAR (e.g. the upper 7 cm of Ware Creek: Figure 4c). This apparent increase in SAR likely does not represent an actual increase in sediment delivery. SAR is calculated by dividing MAR by the dry bulk density of each section, and as the top few centimeters of each creek are poorly consolidated with high porosity, they have a lower dry bulk density than deeper sections. As organic matter degrades and more inorganic sediment is deposited on the creekbed over time, these poorly consolidated sediments will autocompact to a density similar to lower sections and will ultimately be preserved as a lower SAR. Accordingly, MAR likely more accurately reflects the trajectory of sedimentation rates than SAR in the upper 5-10 cm of the CRS profiles.

Land-use and geography

Watershed size, relief, and slope for each creek are presented in Table 2. Land use in 2010 is plotted on Figure 3a as the total area of each land use category, and on Figure 3b as a percentage of the total area of each watershed. Land use through time within each watershed is plotted on Figure 4 along with CRS-modelled sedimentation rates.

Creek Name	Watershed Area (km^2)	Mean top 10% elevation (m WGS84)	Mean bottom 10% elevation (m WGS84)	Watershed Relief (m)	Average Watershed Slope (percent rise)
Oyster	11.76	1.82	-0.48	2.3	3.59
Tusk	1.88	2.13	-0.54	2.7	3.68
Sleepy	5.38	2.96	-0.76	3.7	3.32
Ward	14.96	2.47	0.03	2.4	3.19
Ware	1.54	2.35	-0.14	2.5	3.23
Gales	7.78	10.27	0.79	9.5	4.51
Futch	15.44	13.24	1.36	11.9	4.96
Pages	20.35	14.45	-0.14	14.6	5.10
Howe	14.24	13.09	-0.37	13.5	5.25
Bradley	18.67	12.57	0.08	12.5	4.36
Hewletts	30.23	15.25	0.18	15.1	4.33
Whiskey	8.49	10.39	1.65	8.7	4.93

Table 2. Watershed area, relief, and slope. Creeks arranged geographically from northeast to southwest along the coast: Oyster through Gales are located in Carteret County; Futch through Whiskey are located in New Hanover County.



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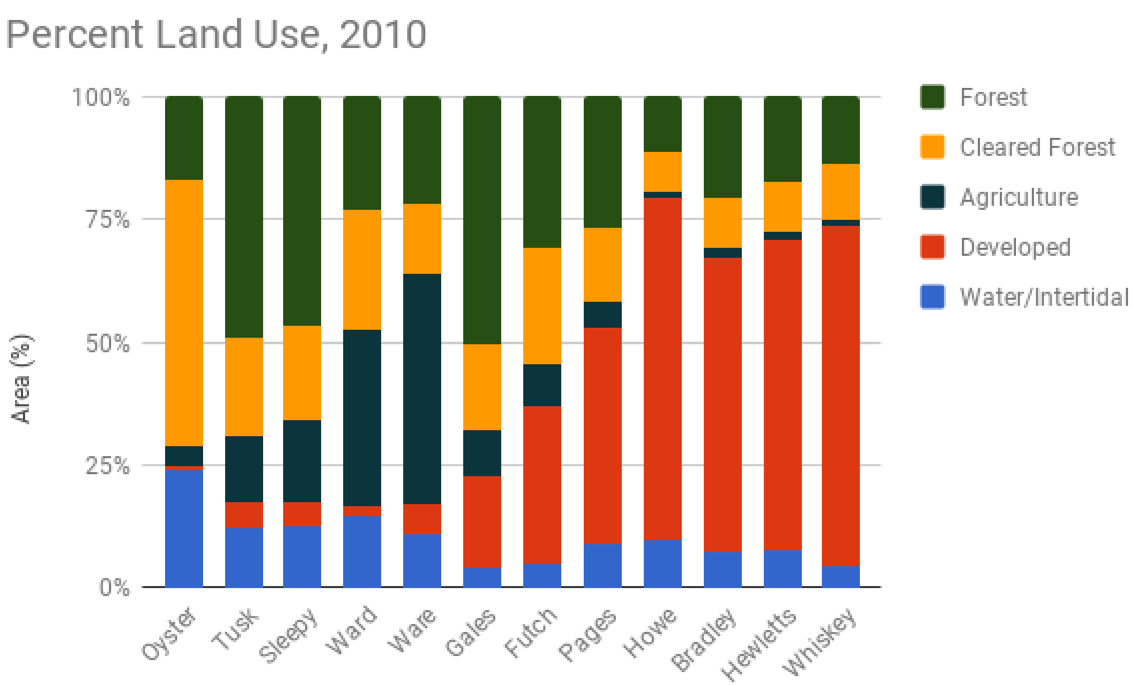

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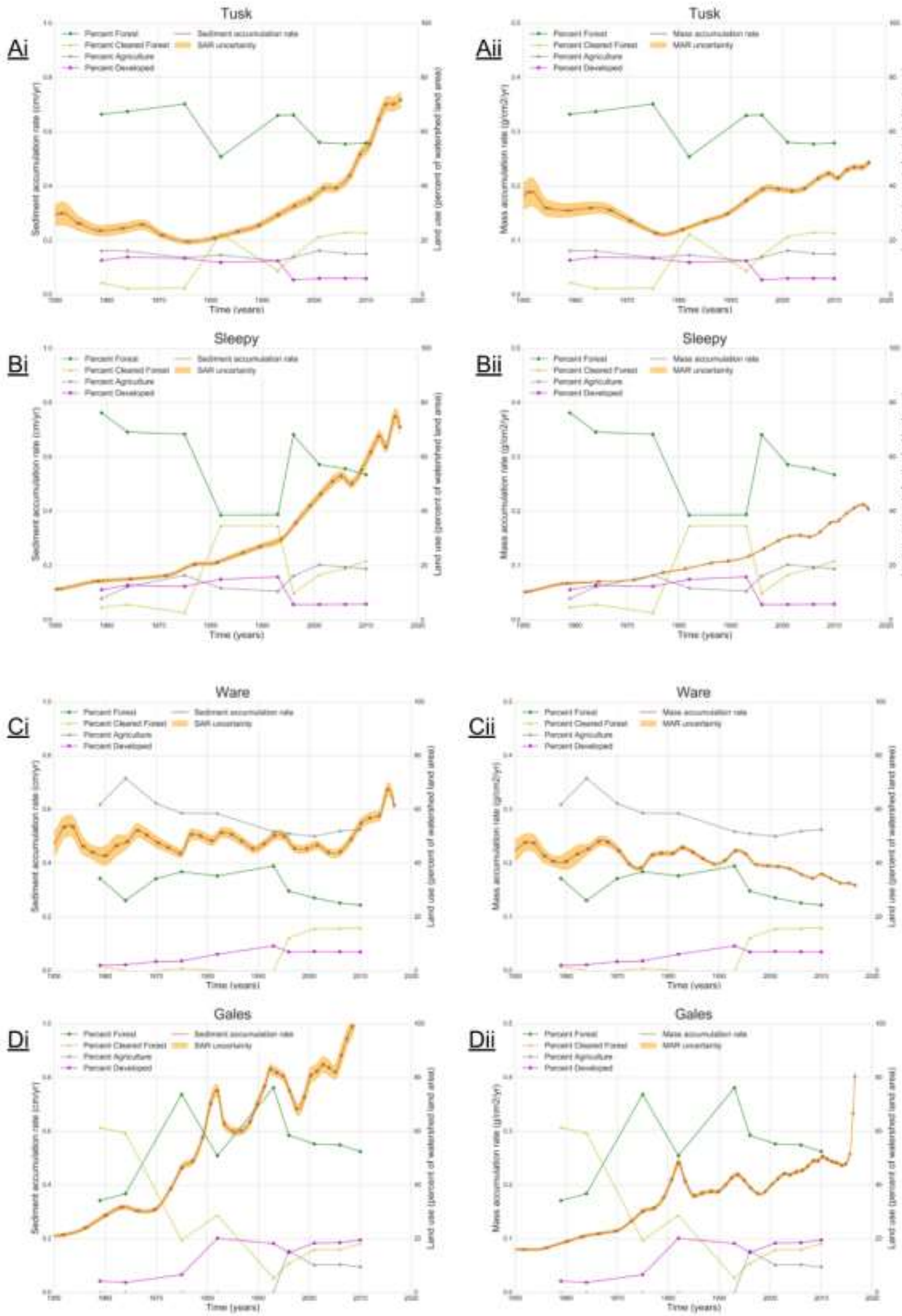
Figure 3. A. Land use in 2010 by creek in square kilometers. B. Land use area in 2010 by creek as a percent of total watershed area. Creeks arranged geographically from northeast to southwest along the coast: Oyster through Gales are located in Carteret County; Futch through Whiskey are located in New Hanover County. Data is provided in Appendix B.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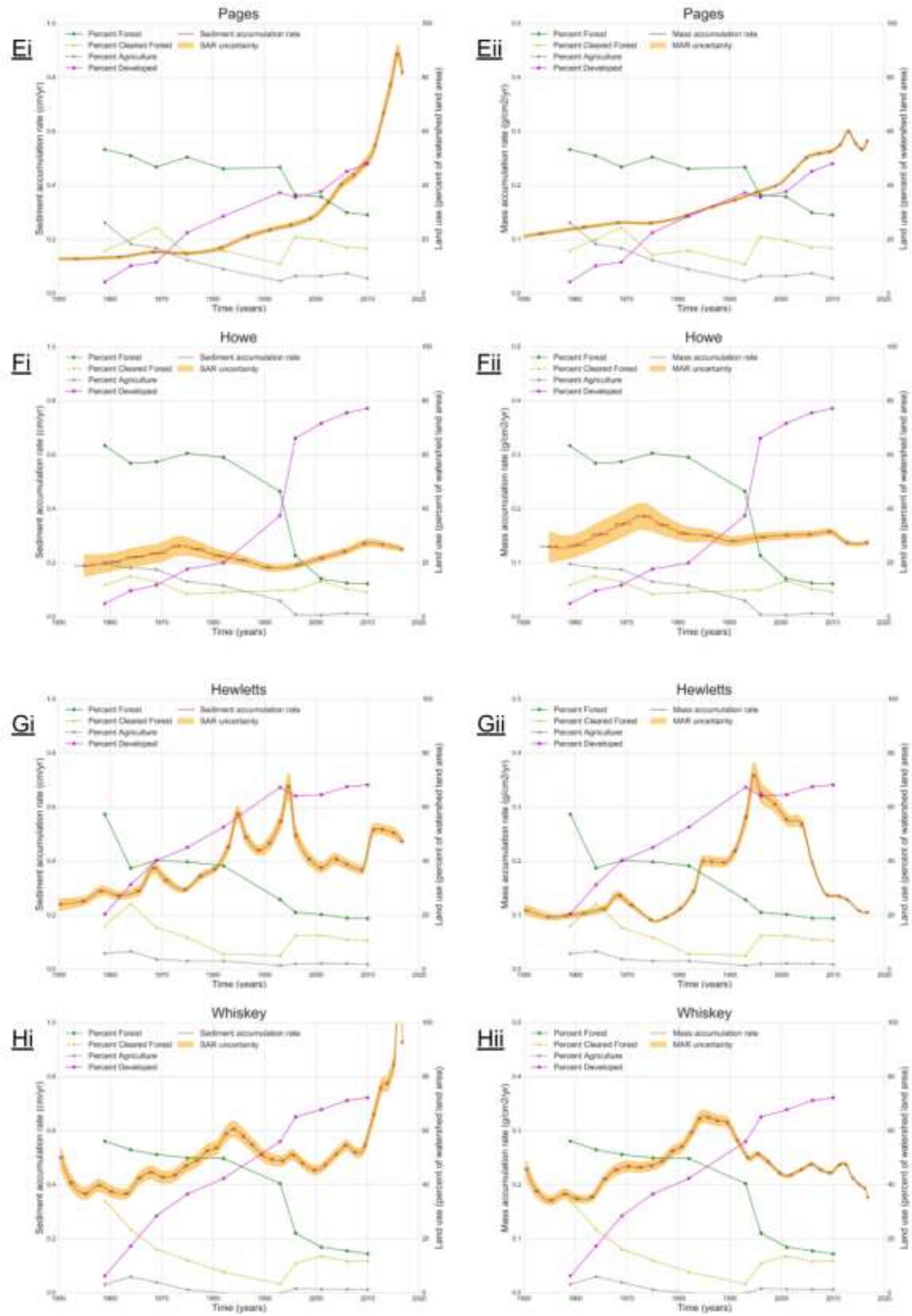
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MAR uncertainty
Mass accumulation rate (g/cm2/yr)
Land use (percent of watershed land area)
Time (years)

Figure 4. CRS-modelled sedimentation rates 1950-2017 and land use as a percent of watershed land area. A: Tusk Creek. B: Sleepy Creek. C: Ware Creek. D: Gales Creek. E: Pages Creek. F: Howe Creek. G: Hewletts Creek. H: Whiskey Creek. A through D are located in Carteret County; E through H are located in New Hanover County. (i) and (ii) denote sediment accumulation rate (SAR) and mass accumulation rate (MAR), respectively. Full-size figures are provided in Appendix C.

The watersheds in Carteret County are generally rural in 2010 (Figure 3), with land use largely consisting of agriculture and forested areas (of which much is used for silviculture), with developed areas making up small proportions of the watersheds. Except for Ware Creek, the Carteret County watersheds had large areas logged during the survey period, and Ward and Ware Creeks have agricultural areas making up 30% and 40% of their watersheds, respectively, which is twice the proportion of all the other creeks. While developed area generally increased through time in Carteret County watersheds, total changes were small (5-15 percent area of individual watersheds) in comparison to forest clearing (20-30 percent area), and were also small compared to the changes in developed area in New Hanover County (up to 70 percent area). Major instances of deforestation occurred between 1975 and 1982 and in the mid-to-late-90s. In Gales Creek (Figure 4d), there are two peaks in sedimentation rate that occur around the same time as these forest clearings, but in Sleepy (Figure 4b) and Tusk Creeks (Figure 4a), no such peaks, or shifts in sedimentation rate, are observed. Ware Creek (Figure 4c), which did not experience sudden large shifts in land use, also does not display sudden changes in sedimentation rates. The Carteret County watersheds generally have lower slopes, except for Gales Creek (which drains part of the Suffolk Scarp), and are smaller in drainage area than the New Hanover County watersheds, except for Oyster and Ward creeks (Table 2).

By contrast, the watersheds in New Hanover County are generally urban/suburban in 2010, with developed areas making up a majority of the southern four watersheds, and increasing through time in all six watersheds. Forested and agricultural areas have shrunk in all six watersheds, largely converting to developed area as the population of the Wilmington, NC metro area has increased and spread outward. Development mostly occurs in the form of large, planned subdivisions, though golf courses are also common, and some commercial areas were constructed along major roads. Development increased continuously in all of these watersheds, and sedimentation rates have also generally increased through time in Pages Creek (Figure 4e: through 2017), Hewletts Creek (Figure 4g: through the mid-1990s), and Whiskey Creek (Figure 4h: through the mid-1980s), although sedimentation rates decline in Hewletts and Whiskey Creek after those maxima, despite constant or increasing levels of development. Sedimentation rates in Howe Creek display no apparent relationship to land-use change, despite having experienced the most rapid increase in development (nearly 50% of the watershed area between 1982 and 1996). The New Hanover County watersheds, which drain across two paleoshorelines, have higher slopes than the Carteret County watersheds, and are generally larger in drainage area.

Discussion

Whole-core CFCS models (Table 1 and Figure 2) indicate that only Sleepy Creek (0.20 cm yr^{-1}) is gaining elevation at a rate less than local relative sea-level rise, while Howe (0.22 cm yr^{-1}) and Pages (0.23 cm yr^{-1}) are within error of the RLSR rate, measured at nearby Wilmington, NC, and the remaining seven creeks exceed RSLR rates. Also including two-segment CFCS and CRS models, all creeks except Howe have SARs exceeding RSLR in recent years (post-2000), indicating that these tidal creeks are infilling and becoming shallower. Shallowing of Bradley and Gales Creeks, which have whole-core CFCS sedimentation rates of 1.8 and 1.2 cm yr^{-1}, respectively, would be very easily noticeable to boaters visiting the creeks repeatedly over a period of years, and may indicate that portions of those creeks that are currently subtidal may soon become intertidal mud flats or be colonized by salt marsh vegetation.

Given disparities in the timing of land use observations (3 to 11 years) and ^{210}Pb-derived dates (CRS: annual to multi-annual; CFCS: multi-decadal), and the potential for temporal lags between changes in land-use and sediment delivery, establishing a predictive time-series relationship is not feasible with our study design. However, given that in three of four CRS-modelled cores from New Hanover County, sedimentation rates experience notable increases through time in tandem with large increases in developed land area, in some cases approaching 70% of the watershed, we can reasonably conclude that increased developed area in coastal watersheds does lead to higher sedimentation rates in tidal creeks.

The CRS sedimentation profiles in Hewletts and Whiskey Creeks initially increase through time, mirroring development, then plateau and begin decreasing. The more recent decrease in sediment-accumulation rates may indicate that the creekbeds have gained enough elevation to reduce channel cross-sectional area, which would increase bed shear stresses and limit further infilling (Friedrichs, 1995), although the recent sedimentation rates are still in excess of RSLR. This may be an indicator that tidal prism in the creeks is decreasing when marshes in the creeks accrete faster than RSLR, which would decrease bed shear stress and allow increased sediment deposition (D'Alpaos et al. 2006); however, this would require a knowledge of sedimentation rates from the adjacent marshes to conclude definitively.

Deforestation is less clearly reflected in sediment accumulation rates in tidal creeks. Changes in sedimentation in Gales Creek appear to roughly align with the dates of forest clearing, indicating that forest clearing may cause pulses of sediment deposition. However, we do not observe immediate shifts in response to silviculture operations that occur in Sleepy or Tusk Creeks. Sedimentation rates in these two creeks do increase through time, possibly in relation to repeated forest clearing, although the magnitude of the response is much less than Mattheus et al. (2009) observed in the nearby Newport River.

Disregarding those creeks that could not be CRS-modelled, the effects of land-use change on sedimentation may in part be moderated by watershed geometry and lithology. Sleepy, Tusk and Ware Creeks are smaller, lower-slope and drain more clay-rich soil than the other creeks in this study (Table 2), so they may be below a threshold size/slope at which land-use change in the watershed is translated into a change in sedimentation rate at the core location. Accordingly, the larger-area, higher-slope, and sandier Gales Creek and the New Hanover County watersheds (with the exception Howe Creek) may be above such a threshold, allowing land-use change to be reflected in sedimentation rates. This may explain why deforestation is linked to increased sedimentation in Gales Creek, but not in the smaller, flatter watersheds of Sleepy and Tusk Creeks.

Distinct event peaks area notably missing from CRS-modelled sedimentation profiles. Only Gales and Hewletts display rapid increases and decreases in sedimentation rate over a short time span, but even those peaks are spread out over several centimeters, representing 5-10 years, rather than sediment deposited over one year or less, as might be expected of the sudden denudation of a large area within the watershed. This may be due to any or a combination of (1) a surface mixing zone, which can dilute tracer concentration peaks, (2) gradual delivery of sediments mobilized by land-use change, or (3) poor preservation of sediment pulses post-deposition due to erosion. Given that only two of eight CRS-modelled creeks have sedimentation peaks at all, it is unlikely that (1) alone is responsible. Mattheus et al. (2009) noted that a transition from unmanaged forest to silviculture in the Newport River watershed, in the northern part of this study region, caused a regime change in sedimentation (using a two-segment CFCS model) immediately following initial forest clearing, rather than after a significant lag time, despite the low gradient of the watershed. While the coastal watersheds in this study are smaller and even lower-relief, and explanation (2) is still possible, the absence of peaks in sedimentation rate in any of our tidal creek cores suggests that explanation (3), post-depositional erosion, is also occurring. As McKee et al. (1983) demonstrated, short-term deposition is not necessarily preserved in long-term accumulated sediments, and sub-annual deposition rates can be an order of magnitude larger than century-scale accumulation rates. Likewise, Sadler (1981) demonstrated that short-term sedimentation rates are a poor guide to longer-term accumulation rates and that completeness deteriorates when considering finer time scales. These concepts demonstrate a potential for a brief increase in sediment deposition to later be eroded, exported out of the tidal creek system, and not reflected in long-term accumulation rates.

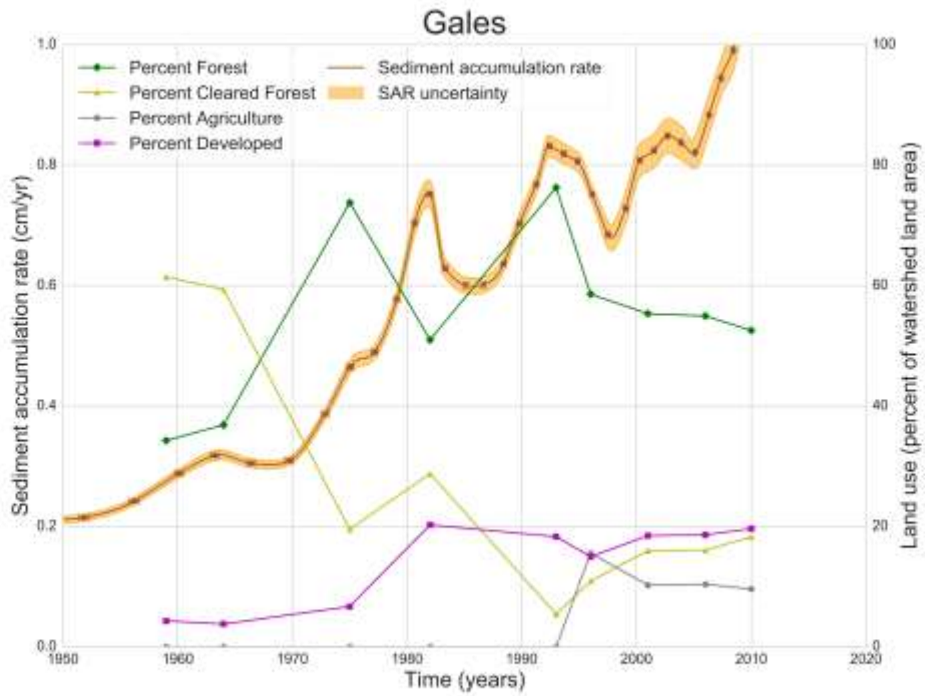
Conclusions

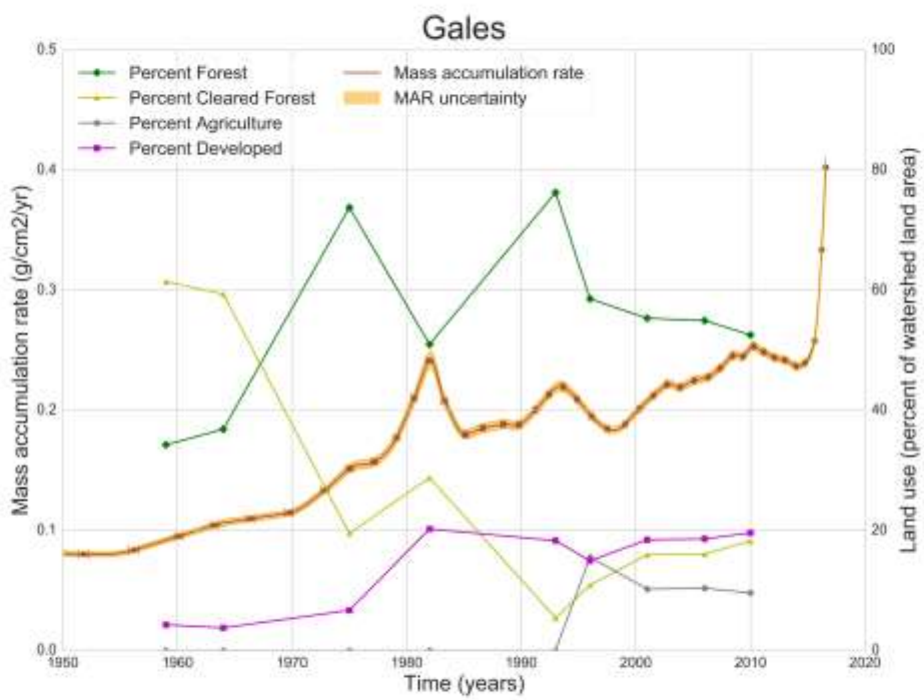
In our 50-year analysis of land-use change and sedimentation in tidal creeks across eastern North Carolina, we have demonstrated that most creeks are infilling at a rate greater than RSLR, and development and deforestation may result in increases in creekbed sedimentation rates in most tidal creek systems. However, the impacts of land-use change may be modulated by tidal hydrodynamics and watershed geometry in some cases. Pulses of sediment are likely to be eroded and exported to downstream estuaries, while long-term increases in sediment supply are more likely to be preserved within the tidal creek systems. Further, these impacts may be better communicated in larger watersheds with steeper slopes. While total infilling of channels is unlikely, increased sediment loads are altering the morphology of tidal creek systems, which will have implications for the ecosystem services they supply, including navigability, quality of fish habitat, and nutrient filtering capacity. Future work should investigate sedimentation rates in tidal creek marshes and changes in creek hydrology, which will be essential for understanding the long-term fate of tidal creeks and the benefits they provide.

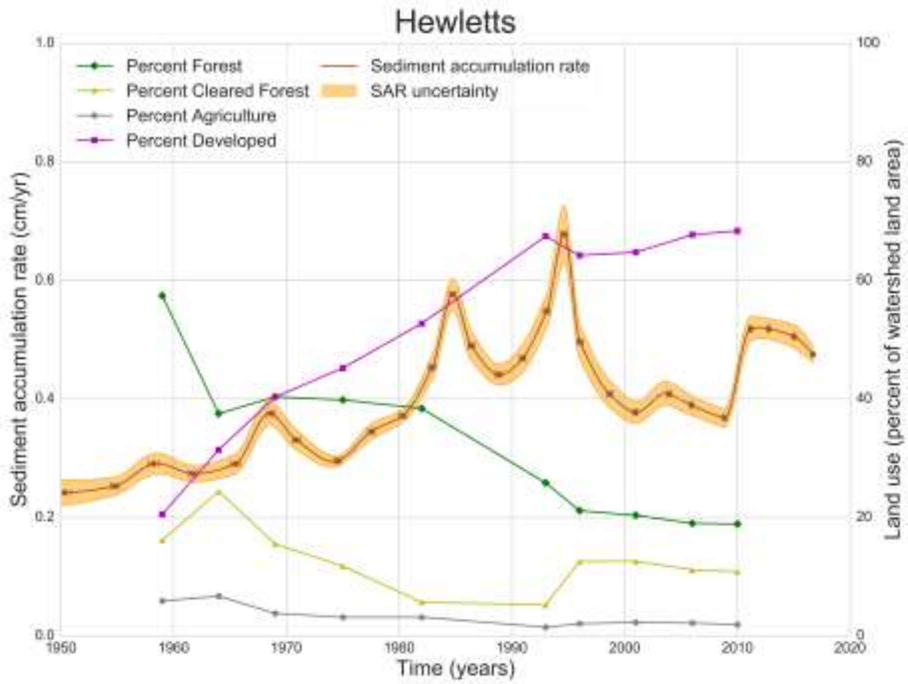
APPENDIX A. LAND USE RECLASSIFICATION SCHEME

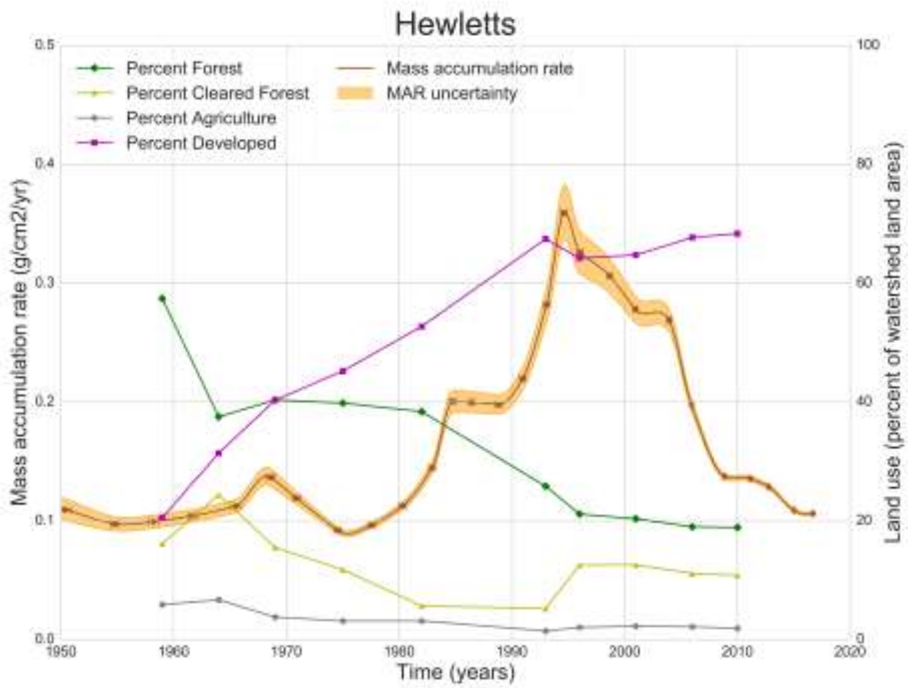
Mapped land use classification	**NOAA CCAP LULC classification**
Developed	Developed, Open Space
	Developed, Low Intensity
	Developed, Medium Intensity
	Developed, High Intensity
Forest	Deciduous Forest
	Evergreen Forest
	Mixed Forest
	Palustrine Forested Wetland
	Estuarine Forested Wetland
Cleared Forest	Scrub/Shrub
	Palustrine Scrub/Shrub Wetland
	Palustrine Emergent Wetland
	Barren Land
Agriculture	Cultivated Crops
	Pasture/Hay
	Grassland/Herbaceous
Water/Intertidal	Open Water
	Palustrine Aquatic Bed
	Estuarine Aquatic Bed
	Estuarine Forested Wetland
	Estuarine Scrub/Shrub Wetland
	Estuarine Emergent Wetland
	Unconsolidated Shore

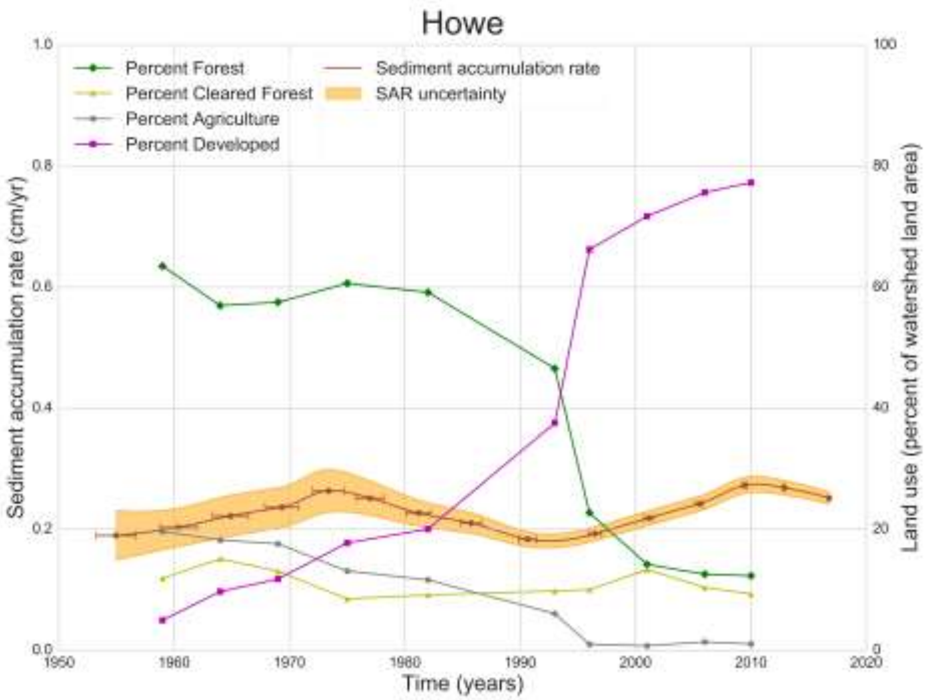
APPENDIX B. LAND-USE CHANGE WITH CRS SEDIMENTATION RATES



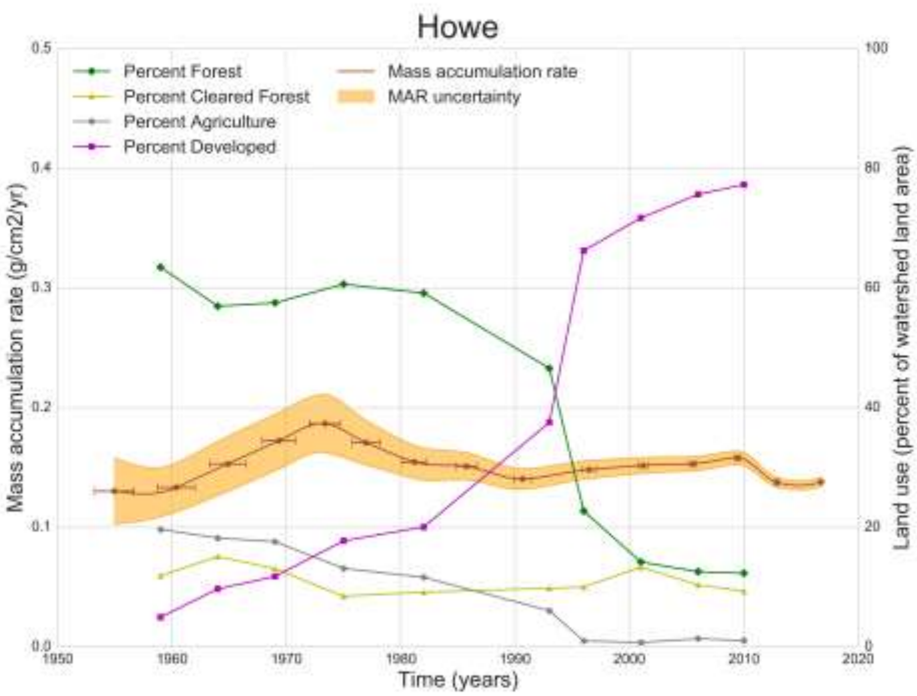



Hewletts
Percent Forest
Percent Cleared Forest
Percent Agriculture
Percent Developed
Sediment accumulation rate
SAR uncertainty
Sediment accumulation rate (cm/yr)
Land use (percent of watershed land area)
Time (years)

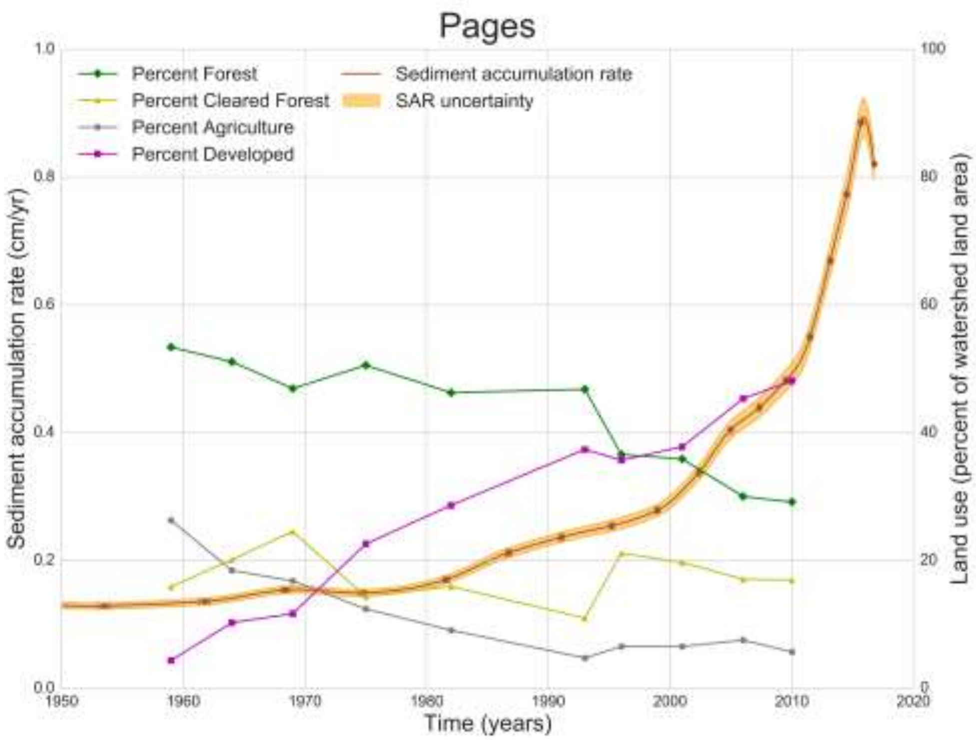

Hewletts
Percent Forest
Percent Cleared Forest
Percent Agriculture
Percent Developed
Mass accumulation rate
MAR uncertainty
Mass accumulation rate (g/cm2/yr)
Land use (percent of watershed land area)
Time (years)

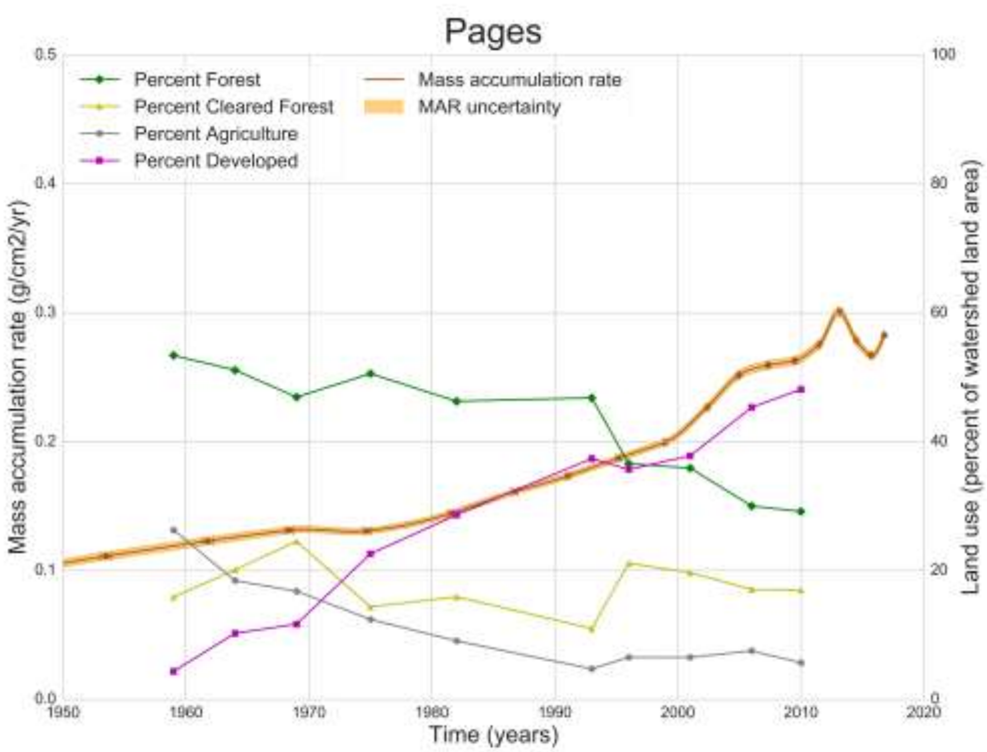


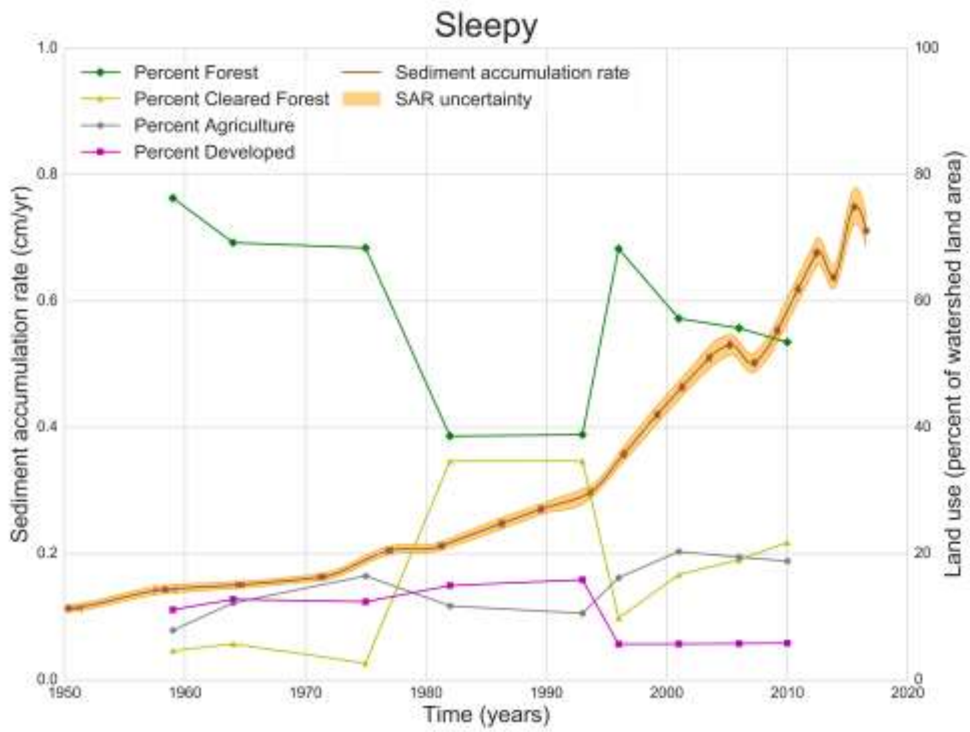
Howe
Percent Forest
Percent Cleared Forest
Percent Agriculture
Percent Developed
Sediment accumulation rate
SAR uncertainty
Sediment accumulation rate (cm/yr)
Land use (percent of watershed land area)
Time (years)

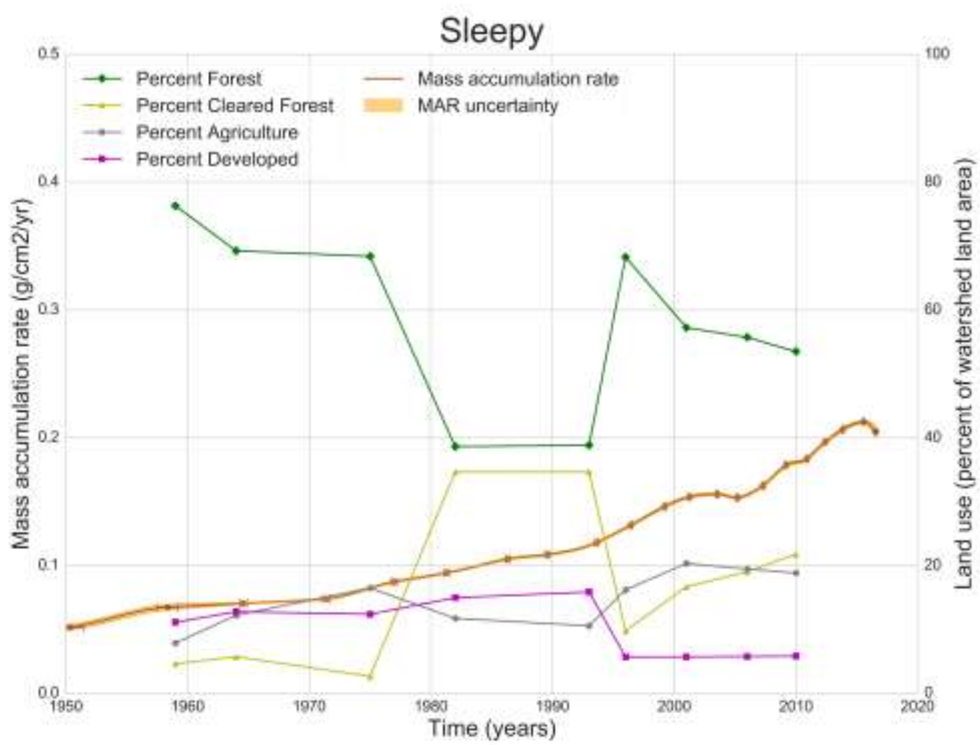


Howe
Percent Forest
Percent Cleared Forest
Percent Agriculture
Percent Developed
Mass accumulation rate
MAR uncertainty
Mass accumulation rate (g/cm2/yr)
Land use (percent of watershed land area)
Time (years)


Pages
Percent Forest
Percent Cleared Forest
Percent Agriculture
Percent Developed
Sediment accumulation rate
SAR uncertainty
Sediment accumulation rate (cm/yr)
Land use (percent of watershed land area)
Time (years)
0.0
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80
100
1950
1960
1970
1980
1990
2000
2010
2020


Pages
Percent Forest
Percent Cleared Forest
Percent Agriculture
Percent Developed
Mass accumulation rate
MAR uncertainty
Mass accumulation rate (g/cm2/yr)
Land use (percent of watershed land area)
Time (years)
0.0
0.1
0.2
0.3
0.4
0.5
0
20
40
60
80
100
1950
1960
1970
1980
1990
2000
2010
2020


Sleepy
Percent Forest
Percent Cleared Forest
Percent Agriculture
Percent Developed
Sediment accumulation rate
SAR uncertainty
Sediment accumulation rate (cm/yr)
Land use (percent of watershed land area)
Time (years)
0.0
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80
100
1950
1960
1970
1980
1990
2000
2010
2020


Sleepy
Percent Forest
Percent Cleared Forest
Percent Agriculture
Percent Developed
Mass accumulation rate
MAR uncertainty
Mass accumulation rate (g/cm2/yr)
Land use (percent of watershed land area)
Time (years)
0.0
0.1
0.2
0.3
0.4
0.5
0
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100
1950
1960
1970
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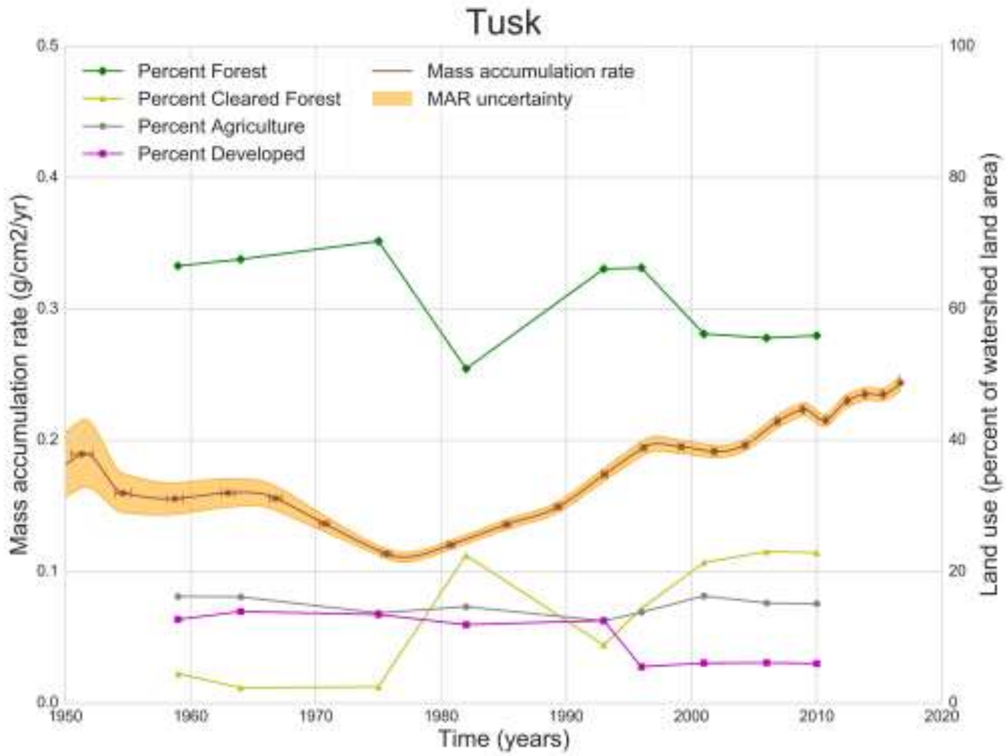
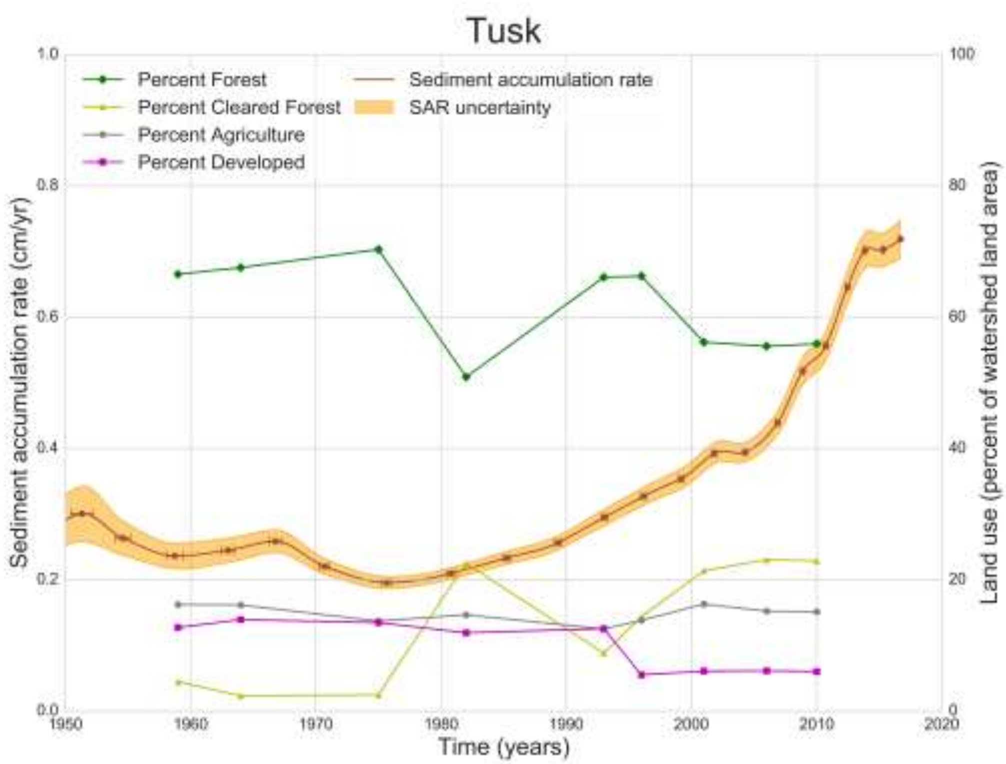
2000
2010
2020


Tusk
Percent Forest
Percent Cleared Forest
Percent Agriculture
Percent Developed
Mass accumulation rate
MAR uncertainty
Mass accumulation rate (g/cm2/yr)
Land use (percent of watershed land area)
Time (years)
0.0
0.1
0.2
0.3
0.4
0.5
0
20
40
60
80
100
1950
1960
1970
1980
1990
2000
2010
2020


Tusk
Percent Forest
Percent Cleared Forest
Percent Agriculture
Percent Developed
Sediment accumulation rate
SAR uncertainty
Sediment accumulation rate (cm/yr)
Land use (percent of watershed land area)
Time (years)
0.0
0.2
0.4
0.6
0.8
1.0
0
20
40
60
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100
1950
1960
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1980
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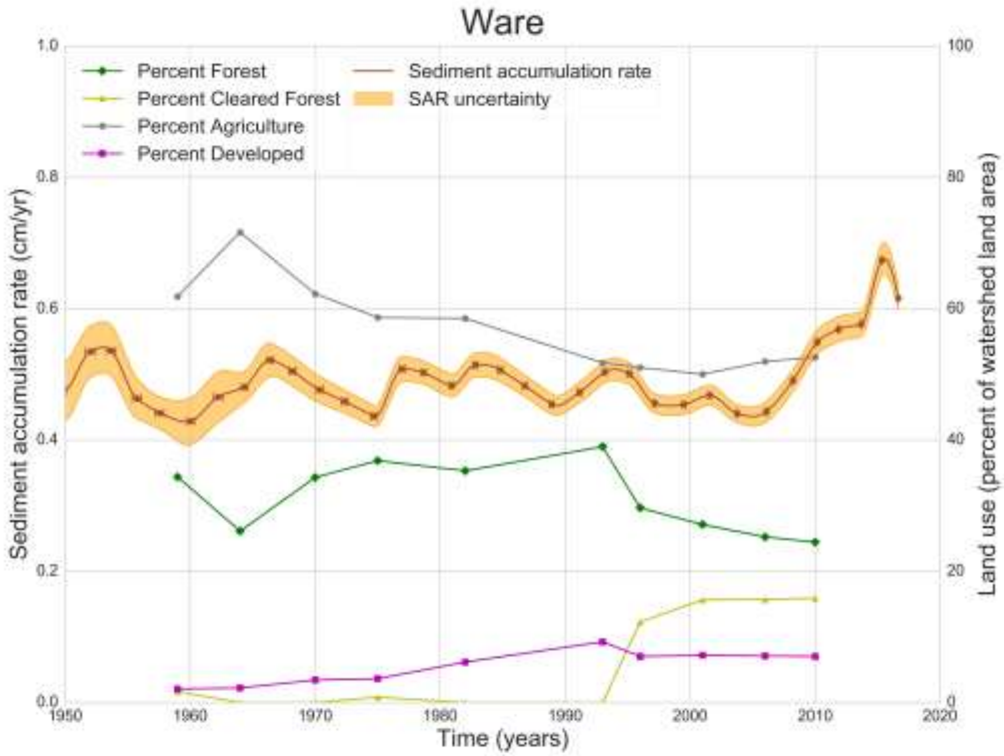
2000
2010
2020


Ware
Percent Forest
Percent Cleared Forest
Percent Agriculture
Percent Developed
Sediment accumulation rate
SAR uncertainty
Sediment accumulation rate (cm/yr)
Land use (percent of watershed land area)
Time (years)
0.0
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80
100
1950
1960
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2000
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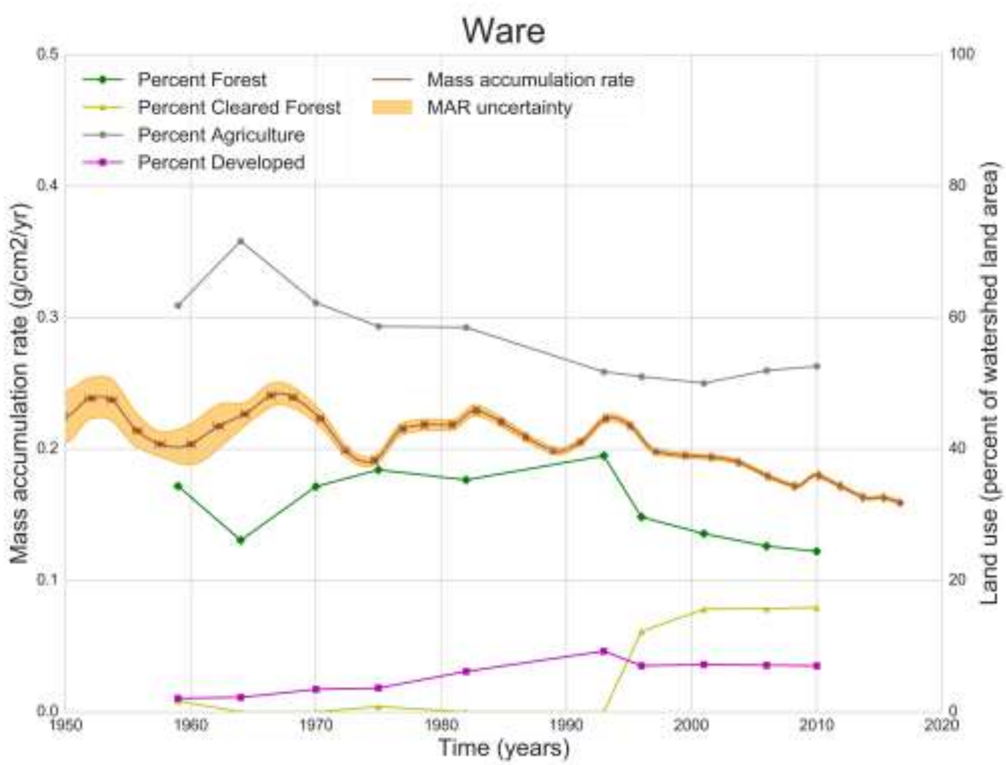
2020


Ware
Percent Forest
Percent Cleared Forest
Percent Agriculture
Percent Developed
Mass accumulation rate
MAR uncertainty
Mass accumulation rate (g/cm2/yr)
Land use (percent of watershed land area)
Time (years)
0.0
0.1
0.2
0.3
0.4
0.5
0
20
40
60
80
100
1950
1960
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1990
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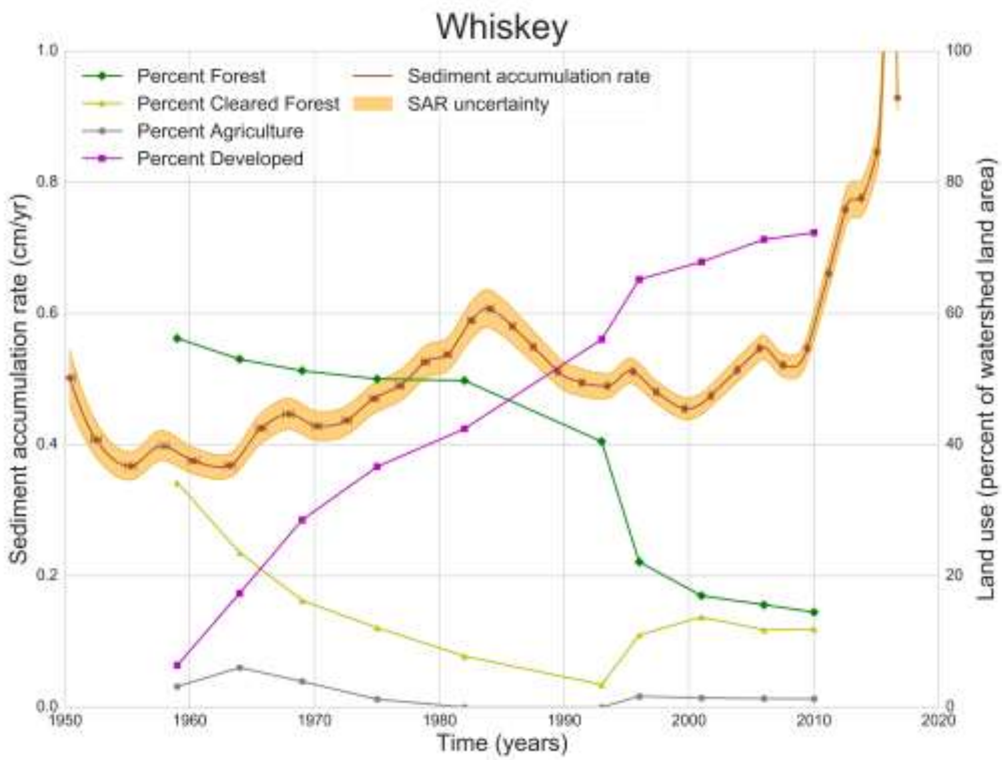
2010
2020


Whiskey
Percent Forest
Percent Cleared Forest
Percent Agriculture
Percent Developed
Sediment accumulation rate
SAR uncertainty
Sediment accumulation rate (cm/yr)
Land use (percent of watershed land area)
Time (years)
0.0
0.2
0.4
0.6
0.8
1.0
0
20
40
60
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100
1950
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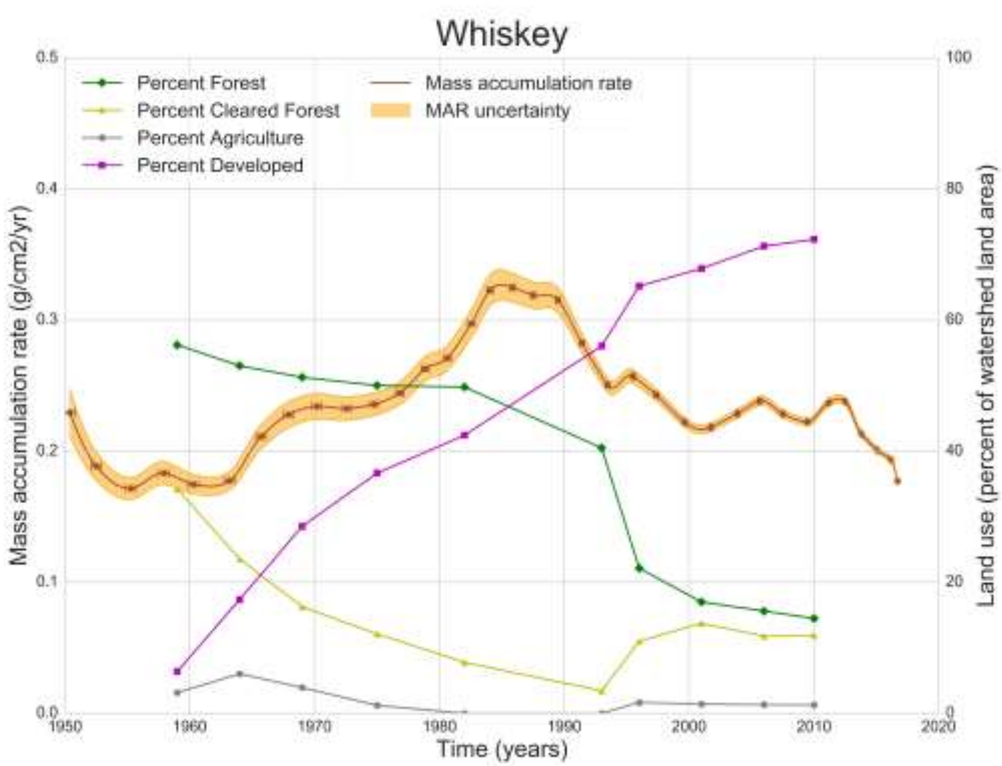
2020


Whiskey
Percent Forest
Percent Cleared Forest
Percent Agriculture
Percent Developed
Mass accumulation rate
MAR uncertainty
Mass accumulation rate (g/cm2/yr)
Land use (percent of watershed land area)
Time (years)
0.0
0.1
0.2
0.3
0.4
0.5
0
20
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100
1950
1960
1970
1980
1990
2000
2010
2020

APPENDIX C: 2010 LAND USE DATA

Land use area in 2010 (square meters)

Creek	Water/Intertidal	Developed	Cleared Forest	Forest	Agriculture
Oyster	2817000	117900	6395400	1973700	465300
Tusk	228600	99900	378900	926100	250200
Sleepy	667800	275400	1027800	2521800	888300
Ward	2205900	298800	3682800	3430800	5342400
Ware	170100	97200	219600	337500	726300
Gales	319500	1462500	1362600	3921300	716400
Futch	722700	5015700	3689100	4736700	1273500
Pages	1835100	8909100	3141900	5397300	1056600
Howe	1404000	9912600	1197000	1580400	136800
Bradley	1347300	11157300	1879200	3870000	401400
Hewletts	2368800	19017900	3017700	5253300	531000
Whiskey	382500	5859000	964800	1174500	103500

Land use area in 2010 (% of total watershed area)

Creek	Water/Intertidal	Developed	Cleared Forest	Forest	Agriculture
Oyster	24%	1%	54%	17%	4%
Tusk	12%	5%	20%	49%	13%
Sleepy	12%	5%	19%	47%	17%
Ward	15%	2%	25%	23%	36%
Ware	11%	6%	14%	22%	47%
Gales	4%	19%	18%	50%	9%
Futch	5%	32%	24%	31%	8%
Pages	9%	44%	15%	27%	5%
Howe	10%	70%	8%	11%	1%
Bradley	7%	60%	10%	21%	2%
Hewletts	8%	63%	10%	17%	2%
Whiskey	5%	69%	11%	14%	1%

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