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PATTERNS AND PROCESS OF SANDBAR REVEGETATION ON THE MISSOURI NATIONAL RECREATIONAL RIVE

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PATTERNS AND PROCESS OF SANDBAR REVEGETATION ON THE MISSOURI NATIONAL RECREATIONAL RIVER

By

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B.Sc., Asian University for Women, 2013

A Thesis Submitted in Partial Fulfillment of
The Requirement for the Degree of
Master of Science

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The members of the Committee appointed to examine the thesis of Amena Begum Ruma find it satisfactory and recommend that it be accepted.

Chairperson, Dr. Mark Dixon

Dr. Mark Sweeney

Dr. David Swanson

Dr. Brennan Jordan

ABSTRACT

Decades of flow regulation have reduced sandbar area and recruitment of cottonwood and willow along the Missouri River. Conflicts exist between managing sandbars for habitat (removing vegetation) for threatened sandbar-nesting birds (i.e., Piping Plover) and allowing natural recruitment of early successional riparian woodland (set-aside bars) that may support other species and ecological values. Recent changes in topography, geomorphology, and vegetation were examined on sandbars that have been "set aside" from management within seven reaches of the Missouri National Recreational River (MNRR) in southeastern South Dakota, USA. An existing time series of maps of sandbar landcover, derived from satellite imagery, was analyzed using ArcGIS to track vegetation and geomorphic changes from 2008-2016. Digital Elevation Models (DEMs) were used to detect elevational changes from 2012-2014/2016, the years following the 2011 flood. Sandbar area was highest on most reaches in 2012 and declined thereafter, and most areas did not show significant elevation changes from 2012-2014/2016. Cottonwood was the most frequent tree species, followed by Russian olive, while sandbar willow was the most abundant shrub species. Redcedar and sweet clover were the most frequent woody and herbaceous invasive plant species, respectively. My findings will inform managers from the National Park Service and US Army Corps of Engineers about how the sandbars in the MNRR have evolved since the 2011 flood. This information is critical for managing the bars in a way that will balance the needs of sandbar-nesting birds and the multiple species of birds and other wildlife that use early successional riparian vegetation.

Thesis Advisor

Dr. Mark D. Dixon

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1. Introduction

Floods carrying sediments and nutrients are crucial for maintaining the health of riparian zones. Historically, the Missouri River had bimodal annual flood peaks – one in April due to the spring ice-out in the upper and middle basin and the second one in June from runoff from melting mountain snowpack. However, flow patterns have been significantly altered by a series of dams and reservoirs constructed during the mid-20th century for flood control, irrigation, hydroelectric power, and downstream navigation (Galat and Lipkin 2000; Pegg et al. 2003). Damming the river altered the Missouri River ecosystem, leading to declines in many aquatic and riparian fauna and flora species, including floodplain forests dominated by plains cottonwood (*Populus deltoides* subsp. *monilifera*) (Johnson et al. 1976, 2012; Dixon et al. 2012). One key impact was a severe decline in emergent sandbar habitat from reduced flooding and a subsequent decrease in sediment transport. Across multiple reaches on the middle and upper Missouri River, sandbar area declined by an estimated 90% from before (1892-1950s) to after (2006) dam construction (Dixon et al. 2012).

Despite these impacts of flow regulation, the Missouri National Recreational River (MNRR), managed by the National Park Service, contains two Missouri River segments with many sandbars. These are known as the 39-mile (downstream of Fort Randall Dam) and the 59-mile (below Gavins Point Dam) segments. Flows and sediment load in each segment are significantly affected by upstream dams, but neither segment is impounded, constrained by levees, or channelized, although each segment is impacted by localized bank stabilization. Despite decades of flow modification, both segments have experienced large flow events in the last 25 years. Sandbars within the MNRR form and evolve along the margins of channels as point bars or within channels as mid-channel or braid bars during high flow events (i.e., floods) and can be emergent when water levels decline (Best et al. 2007).

The largest flood event in the MNRR since 1952 occurred from June to September of 2011, with peak discharges of 4531 cubic meters per second (cms) and a prolonged period of discharges over 2832 cms (Grigg et al. 2011, USACE 2012), compared to a historical median daily discharge value of 850 cms for June-September (1984-2013) at Gavins Point Dam. Erosion and sediment redistribution from the 2011 flood led to an estimated 10-fold increase (from 2006-2012) in emergent sandbar habitat in the MNRR (Dixon et al. 2015). Formation of these bars provided nesting habitat for two federally listed bird species, the (formerly) endangered Interior Least Tern (*Sternula antillarum athalassos*) and the threatened Piping Plover (*Charadrius melodus*) (Nefas et al. 2018). In addition, sandbars created by the flood provided a rare opportunity for widespread cottonwood regeneration, although post-flood recruitment conditions were not optimal and large areas of previously regenerating cottonwood-willow forests were eroded by the flood (Dixon et al. 2015, Johnson et al. 2015).

Sandbar habitat has declined in area in the years since the flood due to erosion and colonization by vegetation. Because of this, the US Army Corps of Engineers (USACE) has sought to maintain or increase the area of remaining emergent sandbar habitat, to protect nesting habitat for the listed bird species, by spraying and clearing vegetation on the bars. However, the National Park Service (NPS) has proposed that at least a subset of the post-flood sandbars should be spared from intensive management (known as “set-aside” sandbars) to support natural growth of the vegetation, including recruitment and early succession of cottonwood-willow forests, on the sandbars (MNRR, 2016). Various successional stages of cottonwood-willow forests support “Outstandingly Remarkable Values” (ORVs) (Mietz, n.d.) for the MNRR, including habitats for woodland wildlife species in the Northern Prairie Region, such as the Bald Eagle and many species of terrestrial birds (Finch and Ruggiero 1993, Swanson 1999, Swanson et al. 2005, Munes et al. 2015). Riparian forests function as corridors and habitat connectors, boosting the mobility of organisms across landscapes and sustaining biodiversity. Riparian vegetation also helps stabilize riverbanks and other geomorphic surfaces (Gurnell et al. 2012; Corenblit et al. 2011). Therefore, acquiring knowledge of the status, trajectories of change, and biological values of these sandbars is essential for informing management by NPS to preserve, protect and enhance these riparian ORVs.

A thorough understanding of the geomorphological processes and vegetation dynamics occurring in these two segments of the Missouri River, including the effects of the flood of 2011 and the period of lower flows since then, is crucial for predicting the continuing evolution of these sandbars and their vegetation. Although the bars were formed by fluvial processes, eolian processes also affect their evolution. Eolian processes initiate the sand mobility on bar surfaces, resulting in dune formation in some places and removal of fine sediments in others, leaving the coarser sediments behind as "gravel lag." With time, the bar becomes stabilized by vegetation colonization and gravel lag (Maxwell 1982). For example, at Macquarie Island in Tasmania, fine sediments were found to be missing from a surface with no lag gravels, which was later stabilized by vegetation (Selkirk et al. 1988). If river discharge does not overtop the sandbars, vertical erosion of the sandbars happens mostly due to the eolian process, whereas fluvial processes are drivers of the lateral erosion and deposition on the sandbars (Sweeney et al., 2019).

In this thesis, I performed analysis of landcover data from pre-and post-flood years to examine how geomorphic and topographic factors affected sandbar formation and vegetation dynamics on seven set-aside sandbar reaches within the MNRR. Time series and change detection maps using satellite and Light Detection and Ranging (LiDAR) imagery from after the 2011 flood were utilized to visualize and quantify possible flood-related changes in landcover on these sites, as well as changes that have occurred in the years following the flood. Differences in site topography among reaches and vegetation types and the relationships between topographic and vegetation changes were examined using overlays of landcover maps and LiDAR-derived elevation maps at vegetation sampling point locations. Vegetation sampling data from field reconnaissance in 2020 were used to understand the composition of early successional vegetation (including tree and shrub density) and invasive species prevalence on the seven set-aside sandbar reaches.

Research Questions

1) To what extent were the changes in landcover on the seven study reaches between 2008-2012 impacted by the 2011 Missouri River flooding?

2) How did the area of vegetation and sandbars formed or reshaped by the 2011 flood change in the years following the flood (e.g., 2012-2016)?

3) How did site geomorphology and topography affect changes in sandbar and vegetation coverage over 2012-2016, and how were geomorphic/topographic changes related to changes in landcover types?

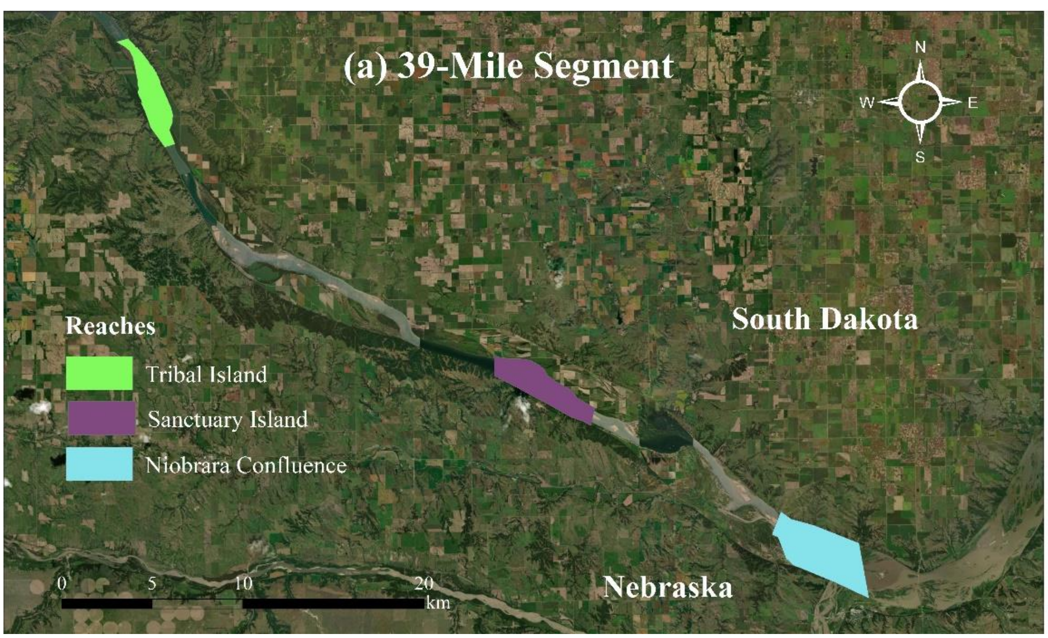
4) What are the dominant tree and shrub species and patterns of woody species richness across the seven focal “set-aside” sandbar reaches?

5) How widely distributed and abundant are several invasive plant species across the focal sandbar sites?

2. Methods

2.1 Study area

The study area consists of seven study reaches containing set-aside sandbars within two unchanneled Missouri River segments (39-mile and 59-mile) within the Missouri National Recreational River (MNRR) in southeastern South Dakota and northeastern Nebraska (Figure 1). The 39-mile segment starts at Fort Randall Dam, near Pickstown, SD, and extends 63 river km to the upper end of Lewis and Clark Lake, near Niobrara, NE. The 59-mile segment begins at the most downstream dam on the river, Gavins Point Dam, near Yankton, SD, and extends downstream 93.5 river km to Ponca, NE. The river is channelized downstream from Ponca. Three study reaches occur in the 39-mile segment: Tribal Island, Sanctuary Island, and Niobrara Confluence. Four reaches occur in the 59-mile segment: Green & Sister Island, James River Island, Goat Island, and Burbank Island (Figure 1).



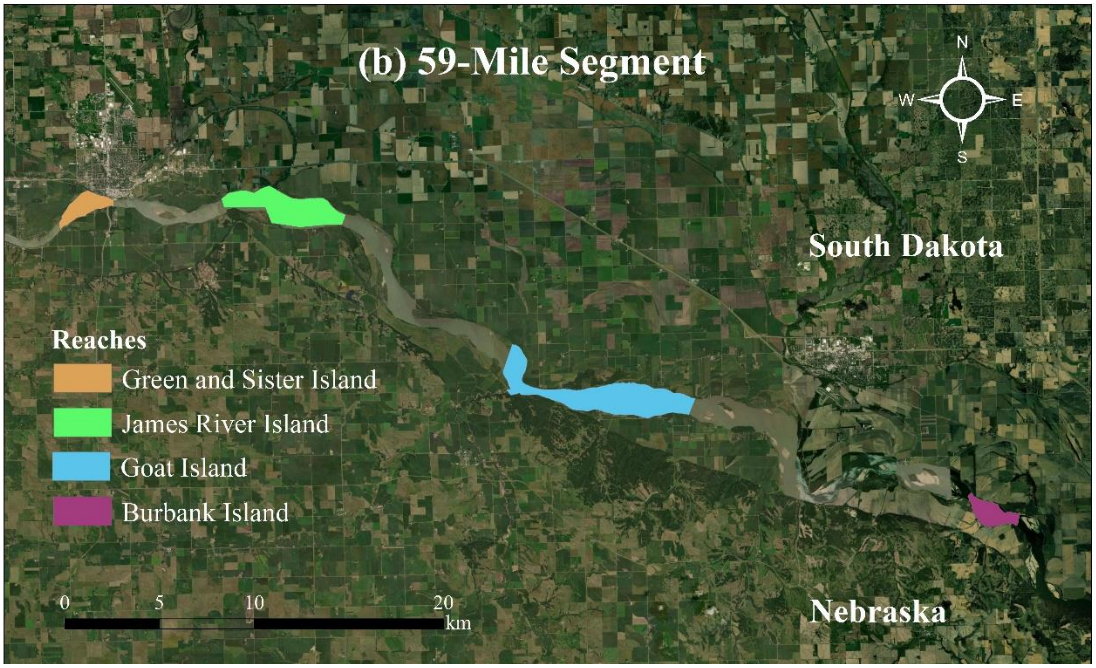


Figure 1: The study sites at seven set-aside sandbar areas on the (a) 39-mile (three reaches) and (b) 59-mile segments (four reaches) of the Missouri National Recreational River (MNRR).

2.2 Vegetation Sampling

Vegetation sampling was conducted at random points within early successional vegetation patches on the seven study reaches in July-August 2020. Using ArcGIS 10.7, I drew polygons inside of these study reaches to delineate areas of early successional riparian vegetation for sampling. Other, unsampled portions of the reaches included mature riparian forests on the mainland and islands. Sampling was also conducted within three of the study reaches in 2019, but these points were resampled in 2020, and the 2019 data were not included in the thesis. Within early successional polygons in each of the seven study reaches, 100 random points were selected in ArcGIS for potential sampling locations and their geographic coordinates (latitude and longitude) transferred to a Garmin GPS. From these candidate points, a subset of 30-40 points were randomly selected for sampling, with points spaced a minimum of 25 meters apart. During sampling, areas with active plover nests were strictly avoided to not scare the birds away from their nests.

Data on vegetation volume, canopy cover, and woody stem density were collected from two nested circles around each point (Figure 2 below). The first circle had a radius of 3 m, within which we estimated an index of foliage volume of the plants up to 5 m in height. The second circle had a 10-m radius within which we estimated the canopy cover of trees with height >5 m. The circles were divided into four quadrants, based on the cardinal directions (N-S, E-W), for estimating vegetation volume or canopy cover into the following cover classes: 0 = 0% (no cover), 1 = 1-33% (sparse), 2 = 33-67% (medium), 3 = 67-100% (high). These cover classes were assessed separately for five different (0-0.5 m, 0.5-2 m, 2-5 m, 5-10 m, and >10 m) vegetation height strata in each quadrant. Dominant woody plant species within each height stratum were recorded for the whole plot.

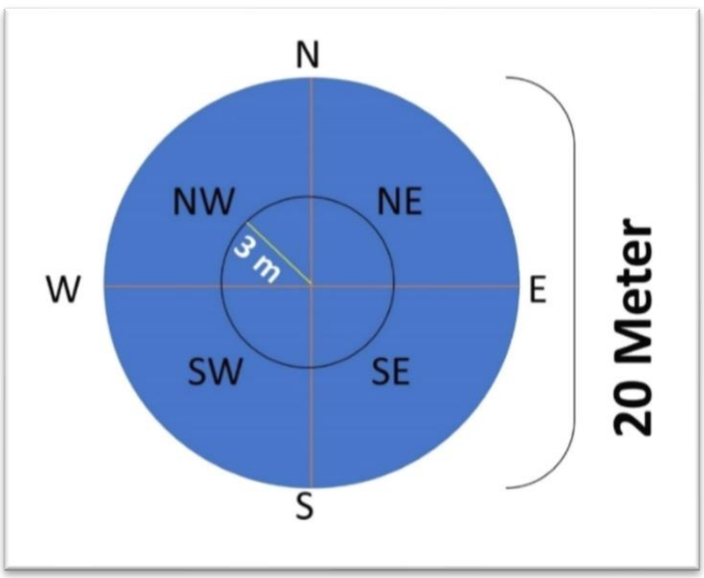


Figure 2: Layout of a vegetation sampling plot.

I classified plants with woody stems, dbh (stem diameter at breast height) ≥10 cm, and height >1.5 m as trees (see Figure B1 in Appendix). All trees present in the 10-m radius plot were tallied, identified to species, and classified into the following size classes by dbh: 10-20 cm, 20-40 cm, 40-80 cm, and >80 cm. Woody plants that were smaller than trees (dbh <10 cm, height >0.5 m) were counted as shrubs/saplings. Shrub/sapling stems were separated into two size classes based on dbh, <2.5 cm and 2.5-10 cm, and were tallied by size classes and species within the 3-m radius plot. Stems were noted as live or dead. Distances were measured using measuring tapes, if necessary, to verify that recorded trees or shrubs occurred within the respective plot radii. Stems of shrubs or trees chewed off by beavers (such that they would not otherwise count as shrubs or trees according to our criteria) were also noted and recorded separately by size class and species.

I also noted the abundance of ten focal invasive species (six herbaceous and four woody) within each 10-m-radius plot. The herbaceous species included common reed (*Phragmites australis)*, purple loosestrife (*Lythrum salicaria*), sweet clover (*Melilotus officinalis*), reed canary grass (*Phalaris arundinacea*), leafy spurge (*Euphorbia esula*), and Canada thistle (*Cirsium arvense*). The invasive woody species were salt cedar (*Tamarix ramosissima*), Russian olive (*Elaeagnus angustifolia*), eastern redcedar (*Juniperus virginiana*), and Siberian elm (*Ulmus pumila*). For each species, I estimated ground or canopy cover within the plot within five cover codes: 0 = 0% (none), 1 = <1% (trace), 2 = 1-10%, 3 = 10-33%, 4 = 33-67%, 5 = 67-100% (dominant). For the woody invasive species, I also noted if the cover occurred in multiple growth forms (e.g., seedling, sapling, and tree).

2.3 Vegetation time-series mapping

I obtained digital maps of landcover for the MNRR for the years 2006-2019 from the US Army Corps of Engineers (USACE) in Yankton, SD. The maps were stored in raster format as feature classes in ArcGIS geodatabases for each year and segment of the MNRR (i.e., Fort Randall vs. Gavins Point segments). The maps included several feature classes that provided different scales of habitat detail. I used the "Landcover" feature class because it provided the highest level of detail in delineating landcover types. For my analysis, I excluded upland habitat types and only used the riverine/riparian cover types related to vegetation, sandbar area, and water. The 2016 maps did not delineate the 'forest' category, so I had to digitize it for that year from the previous (2014) maps. The maps were originally developed by the US Geological Survey (USGS) for mapping sandbar habitat of the threatened bird species from summer high resolution satellite imagery (Quickbird, GeoEye, WorldView, and RapidEye), using object-based image analysis of different classes of sand and vegetation density (Strong 2012). A list of image sources with satellite name, date, resolution, and river flow information is provided in the appendix (see Tables A3 and A4).

For historical time series analysis, I used landcover maps for 2008, 2012, 2014, and 2016. I did not include the most recent data (i.e., years 2018, 2019), because LiDAR was not available beyond 2016, and flows were higher in 2018 and 2019, potentially covering some of the sandbar area. The latter three years (2012, 2014, 2016) were chosen because they approximately matched the dates for LiDAR imagery that I used to evaluate topographic change. In some cases, alternative years had to be used, as the imagery for some years and locations was obscured by visible cloud cover. For example, for Green & Sister Island, James River Island, and Burbank

Island, I used 2009 instead of 2008. For Goat Island, I used 2015 instead of 2014 (see Table A1 in the Appendix A).

For each year, I used the boundaries of each study reach to extract the desired area from the landcover maps. I used the ‘dissolve tool’ in ArcGIS to merge similar landcover categories. I combined the original, more detailed landcover categories into six new habitat categories: high, moderate, and low canopy cover vegetation; forest; sandbar; and water (see Table 1 below for original and reclassified land cover types). Finally, I calculated the total area for each category by using the calculate geometry tool in ArcGIS.

Table 1: Landcover types used in time series and vegetation change detection analysis.

Landcover types	Final Categories	Original Landcover Categories
Vegetation	Forest	ISL large trees, ISL woody dominated, FP closed forest and FP woodland
	High canopy	ISL high canopy cover, high biomass herbaceous and woody seedlings and saplings and FP cropland
	Low canopy	ISL low canopy cover herbaceous and woody seedlings and saplings
	Moderate canopy	ISL moderate canopy cover, low biomass herbaceous and woody seedlings and saplings
Sandbar	Sandbar	ISL wet substrate sparse vegetation, ISL dry sand and ISL wet sand
Water	Water	Water

*ISL= Island and FP=Flood Plain

Transitions in landcover types between years were examined visually and quantified via map overlays for 2012-2016 for the study reaches in the 39-mile segment and for 2012-2014 for those in the 59-mile segment. These dates were chosen because they coincided with the years for which topographic maps derived from LiDAR were available on each segment. The six landcover types were combined into three broader categories - vegetation, water, and sandbar (Table 1) - to map and quantify transitions. I combined forest and high, moderate, and low canopy into "vegetation" and left the sandbar and water categories unchanged. After renaming the categories, I added a new field in the attribute table, used the 'field calculator', and applied the equation: (past year of land cover types) + " – " + (recent year of land cover types). The new field shows how past landcover categories converted into new categories between the time periods (e.g., see Figure B2 in the Appendix). Then I used the calculate geometry tool to calculate the changes in landcover area.

2.4 Topographic and Geomorphic Change Analysis

I analyzed topographic changes within each study reach in two different ways. First, I used ground elevation data from LiDAR (Light Detection and Ranging) to quantify topographic changes on sandbar sites from 2012-2014/2016. I obtained 1-m Digital Elevation Models (DEM) for the years 2012 and 2014 for the 59-mile segment and for 2012 for the 39-mile segment from the USACE. I created a DEM for 2016 for the 39-mile segment using .las files obtained for the respective South Dakota and Nebraska counties. For the South Dakota side on the 39-mile segment (Charles Mix and Gregory counties), I obtained the 2016 .las files from Mr. Kevin Wegenke, SD State GIS Coordinator. For the Nebraska side (Boyd and Knox counties), I received 2016 .las files from Shandy Bittle, State GIS Specialist for Nebraska. The vertical resolution ranged from 6.9 to 18.5 cm and horizontal resolution ranged from 60 to 100 cm for the 2012, 2014 and 2016 LiDAR imagery (see Table A5 in Appendix A).

I used the 'raster calculator' tool in ArcGIS and calculated topographic change by subtracting the pixel elevations from the 2012 DEM from those on the 2014/2016 DEM. After calculating the elevation change between years, I added break values using a manual classification method with 12 classes. I calculated the threshold value as ±0.22 m for statistically significant topographic change, based on the equation offered by Wheaton et al. (2010). Hence, I used 0.44 m intervals and put break values at -2.42, -1.98, -1.54, -.1.10, -0.66, -0.22, +0.22, +0.66, +1.10, +1.54, +2.42 m. I overlaid this elevation change map with the landcover change map to explore the relationships among geomorphic, vegetation, and topographic changes.

I analyzed the relationships among vegetation changes, topography, and geomorphic changes at the point locations of vegetation plots sampled during summer 2020. I compared 1) the relative elevations (elevation above water surface) of different mapped vegetation types, 2) relative elevations of all plots in the seven study reaches, and 3) changes in elevation across different landcover change types. I created a data file of sampling points containing several variables, including the name of the reach (i.e., Tribal Island, Green & Sister Island, etc.), the landcover types for years 2012 and 2016, and the elevations in 2012 and 2014/2016. I extracted the elevation of each sampling point by using 'extract multi-values by point' in ArcGIS. To obtain erosion and deposition information for each sampling point, I subtracted the 2012 elevation from the 2014 or 2016 elevation, depending on the river segment. To compute relative elevation, I first calculated the mean water level for each study reach on the year 2012 DEM (since both segments had 2012 LiDAR), based on 10 random points across the main channel. Then I subtracted the mean 2012 water level on each reach from the sampling point elevations in

2012 and 2014/2016. I also calculated 2014 and 2016 mean water levels in the same way that 2012 water levels were calculated but did not use these to compute relative elevation (Table A6 and A7).

I reclassified the previous landcover transition categories into four new categories to examine the relationship of landcover change to topographic changes: remain sandbar (sandbar-sandbar), remain vegetation (vegetation-vegetation), lost vegetation (vegetation-water and vegetation-sand) and new vegetation (water-vegetation and sand-vegetation). I documented all this information in a spreadsheet and used that data file for further analysis.

2.5 Statistical analysis using sampling points

I compared 1) the relative elevations of the original mapped landcover types (i.e., high canopy, moderate canopy, low canopy, forest, and sandbar) in years 2012 and 2014/2016, 2) the relative elevations of plots in the seven study reaches, and 3) the mean elevation change (erosion and deposition) across 2012-2014/2016 by landcover change type (new vegetation, remain sandbar, remain vegetation, and lost vegetation) using one-way ANOVA, with Tukey-Kramer post-hoc tests to explore pairwise differences. All statistical analyses were conducted using R for Windows with statistical significance defined as $p < 0.05$.

3. Results and Analysis

In this section, I have highlighted the results of my study. I have divided this section into four main parts. First, I quantified landcover changes for each study reach across the time series of sandbar maps, examining the effects of the 2011 flooding and subsequent changes on vegetation and sandbar area. Next, I inspected the DEMs created from the LiDAR imagery and used the sampling point locations from my field survey to explore the relationships among relative elevation, original vegetation type, and vegetation change categories. Then I examined some key factors, such as aggradation and erosion, related to geomorphic and topographic changes that affected the sandbar and vegetation formation in the MNRR. Finally, I reported the composition of woody vegetation (trees and shrubs) and the abundance of ten focal invasive plant species on the vegetation sampling plots across the seven study reaches.

3.1 Temporal Changes in Vegetation and Sandbar Area

3.1.1 Time series of landcover changes from 2008-2016

To visualize the landcover changes from 2008-2016, I prepared a time series of maps for each of the seven study reaches across the 39-mile and 59-mile segments. Given the strong effect of the 2011 flood, longitudinal analysis of landcover maps (Figure 3, 4 and 5) for the reaches on the 39-mile segment show an overall increase in sandbar area, particularly by 2012. However, the three study sites in the 39-mile segment show a mixed pattern for vegetation categories. For example, Tribal Island experienced an overall decrease of 28.4 ha (55% decrease) in forest area from 2008-2016, but the remaining classes (i.e., high canopy, low canopy, moderate canopy) experienced increases in total area (Table 2). Sanctuary Island experienced an overall increase in forest of 43.2 ha, an increase in low canopy, and decreases in the high and moderate canopy cover classes by 10.1 and 25.4 ha, respectively (Table 3). Finally, for Niobrara Confluence, forest and high canopy cover vegetation decreased in area by 108.7 ha and 124 ha, whereas low and moderate canopy areas increased by 10.6 ha and 36.8 ha from 2008-2016 (Table 4). In summary, for reaches in the 39-mile segment, I observed an overall increase in the low canopy and sandbar areas from 2008-2016. Forest area and high canopy each decreased on two of the three reaches, and moderate canopy increased on two of the three. Among the three reaches in the 39-mile segment, Niobrara Confluence had the highest reduction in forest and high canopy area and highest increase in sandbar area from 2008-2016.

Similar to the reaches on the 39-mile segment, the four study reaches in the 59-mile segment also experienced an overall increase in sandbar area from 2008-2016, with James River Island showing the largest net increase, at 61.7 ha (Figure 6, 7, 8 and 9). However, changes in the vegetation categories differed among the study reaches. Green & Sister Island experienced an overall decrease in forest and high canopy, while the low and moderate canopy classes increased (Table 5). James River Island experienced a decline in the high canopy by 43.3 ha but an increase in all other vegetation categories (Table 6). Goat Island showed a decrease in high, moderate and low canopy cover classes of vegetation but an increase in forest area from 2008-2016 (Table 7). Burbank Island shows a decrease in moderate canopy of 15.3 ha from 2008-2016, but an increase in the other vegetation categories (Table 8).

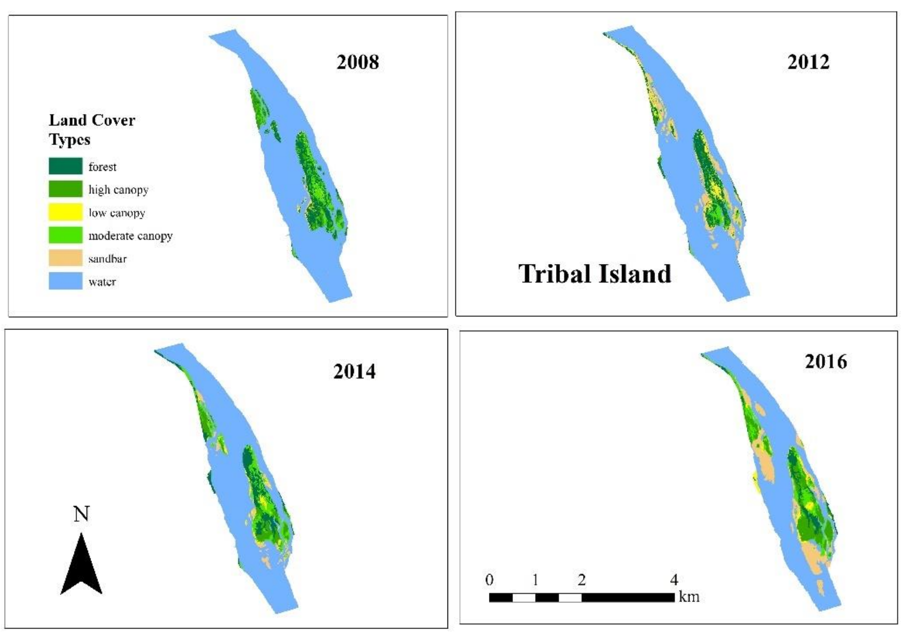


Figure 3: Land cover types change map for Tribal Island in the 39-mile segment of the MNRR (2008-2016).

Table 2: Changes in area of different landcover types for 2012-2016 at the Tribal Island study reach

Category	2008 (ha)	2012 (ha)	2014 (ha)	2016 (ha)
Forest	51.9	52.6	46.2	23.4
High canopy	27.3	10.2	31.4	71.8
Low canopy	4.2	21.6	8.8	10.9
Moderate canopy	35.9	15.0	48.5	44.0
Sandbar	4.7	49.4	20.8	83.3
Water	473.9	460.6	453.0	372.3
Total Area	597.8	609.5	608.8	605.1

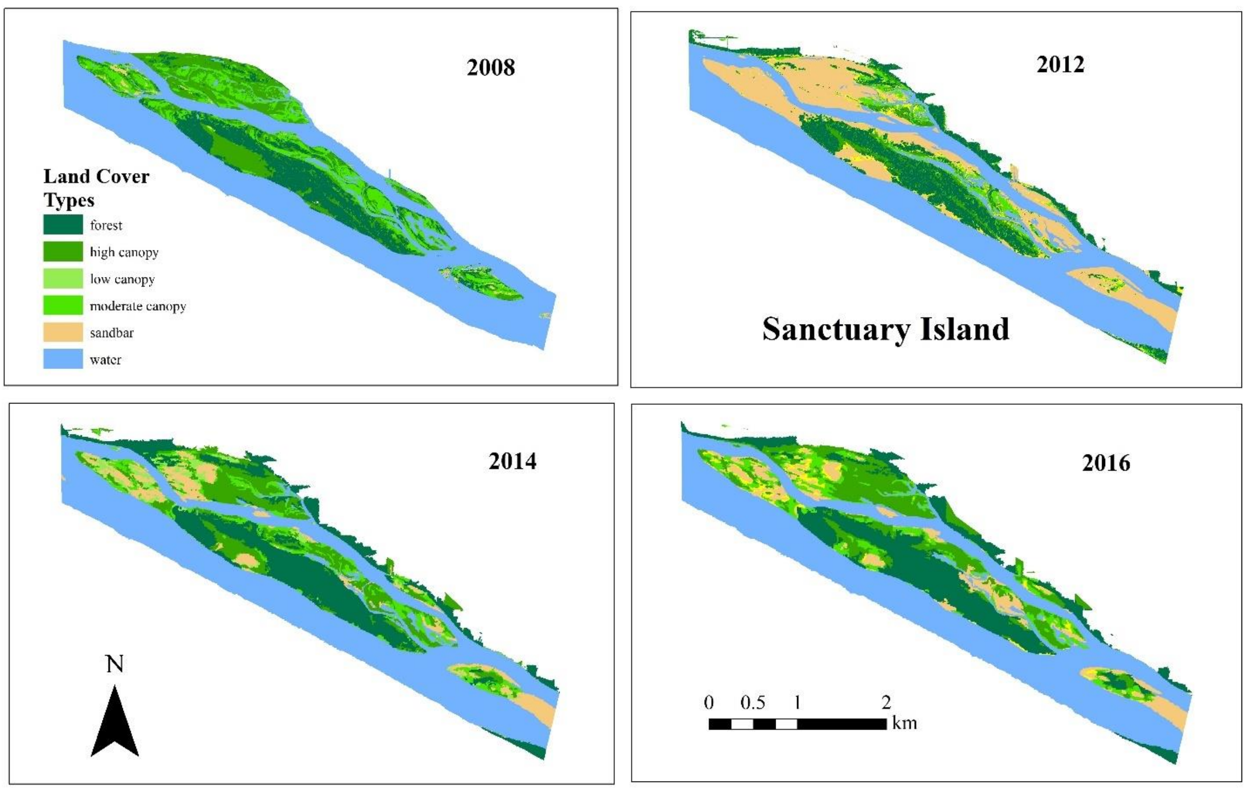


Figure 4: Land cover types change map for Sanctuary Island in the 39-mile segment of the MNRR (2008-2016).

Table 3: Changes in area of different landcover types for 2008-2016 at the Sanctuary Island reach.

Category	2008 (ha)	2012 (ha)	2014 (ha)	2016 (ha)
Forest	85.7	104.0	134.3	128.9
High canopy	106.1	35.8	91.1	95.9
Low canopy	0.3	20.2	17.1	11.6
Moderate canopy	77.3	26.6	46.2	51.9
Sandbar	5.9	148.5	49.3	53.1
Water	346.7	329.0	326.8	326.0
Total Area	621.9	664.1	664.8	667.5

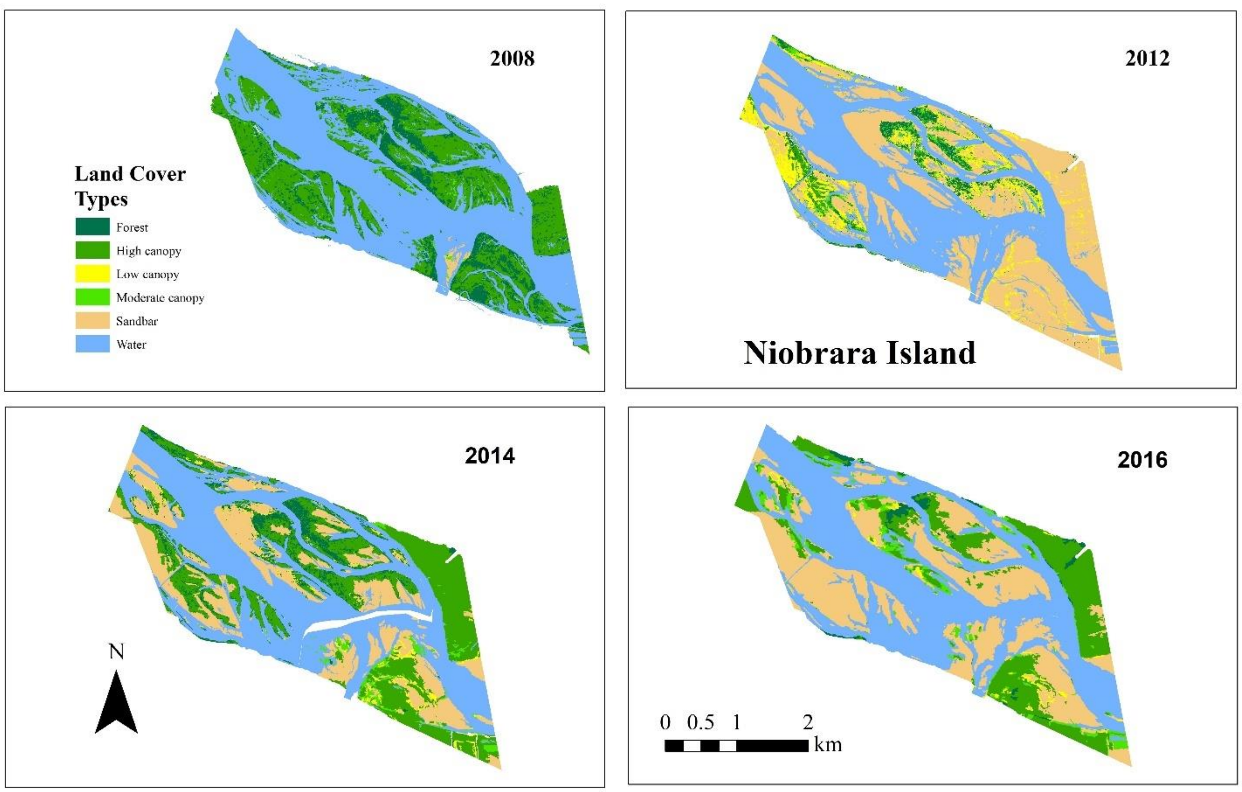


Figure 5: Land cover types change map for Niobrara Confluence in the 39-mile segment of the MNRR (2008-2016).

Table 4: Changes in area of different landcover types for 2008-2016 at the Niobrara Confluence reach

Category	2008 (ha)	2012 (ha)	2014 (ha)	2016 (ha)
Forest	125.6	39.1	72.2	16.9
High canopy	335	19.8	283.7	210.4
Low canopy	0.1	91	18.5	10.7
Moderate canopy	10.4	26.4	24.5	47.2
Sandbar	5.9	472	265.3	365.5
Water	614.3	538.2	507.9	532.7
Total Area	1091.3	1186.5	1172.1	1183.4

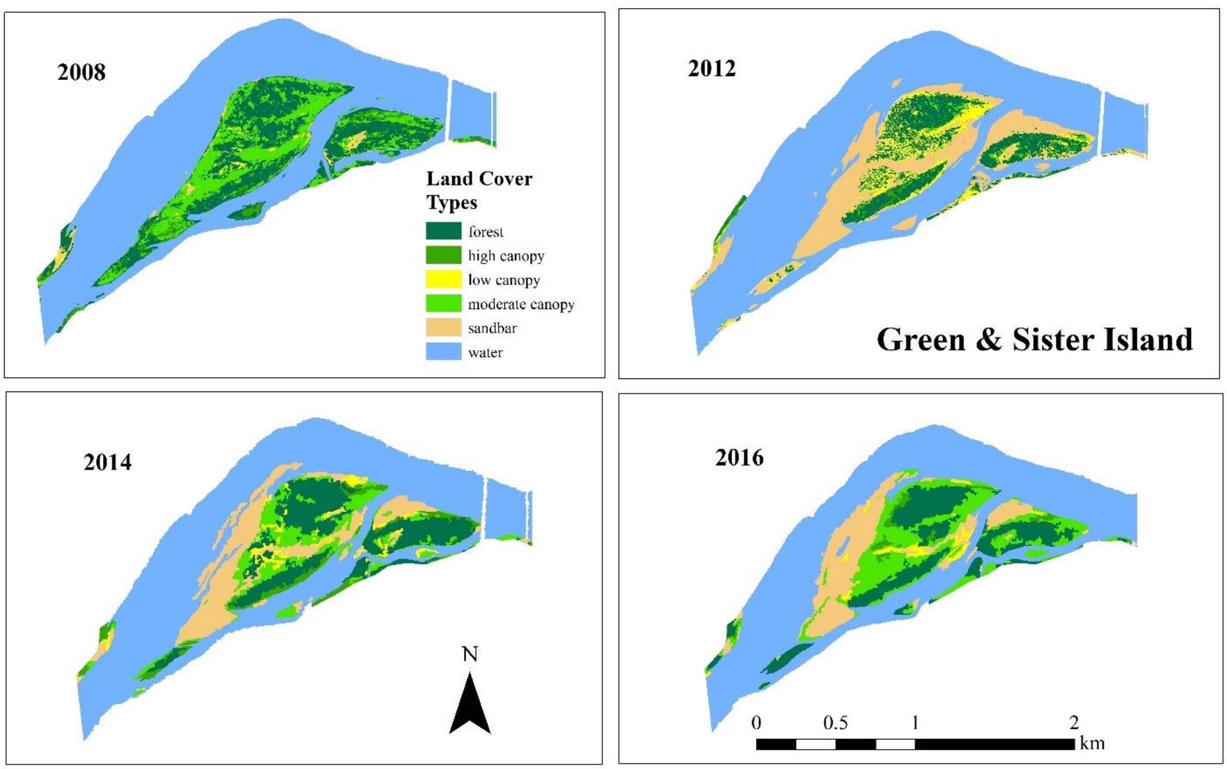


Figure 6: Land cover types change map for Green & Sister Island reach in the 59-mile segment of the MNRR (2008-2016)

Table 5: Changes in area of different landcover types for 2008-2016 at the Green & Sister Island reach.

Category	2008 (ha)	2012 (ha)	2014 (ha)	2016 (ha)
Forest	40.0	25.7	29.7	29.8
High canopy	7.1	2.2	6.8	3.8
Low canopy	1.9	14.5	12.4	3.4
Moderate canopy	30.1	2.7	14.1	32.4
Sandbar	2.1	39.9	30.3	29.6
Water	149.5	148.5	140.2	134.5
Total Area	230.7	233.5	233.5	233.5

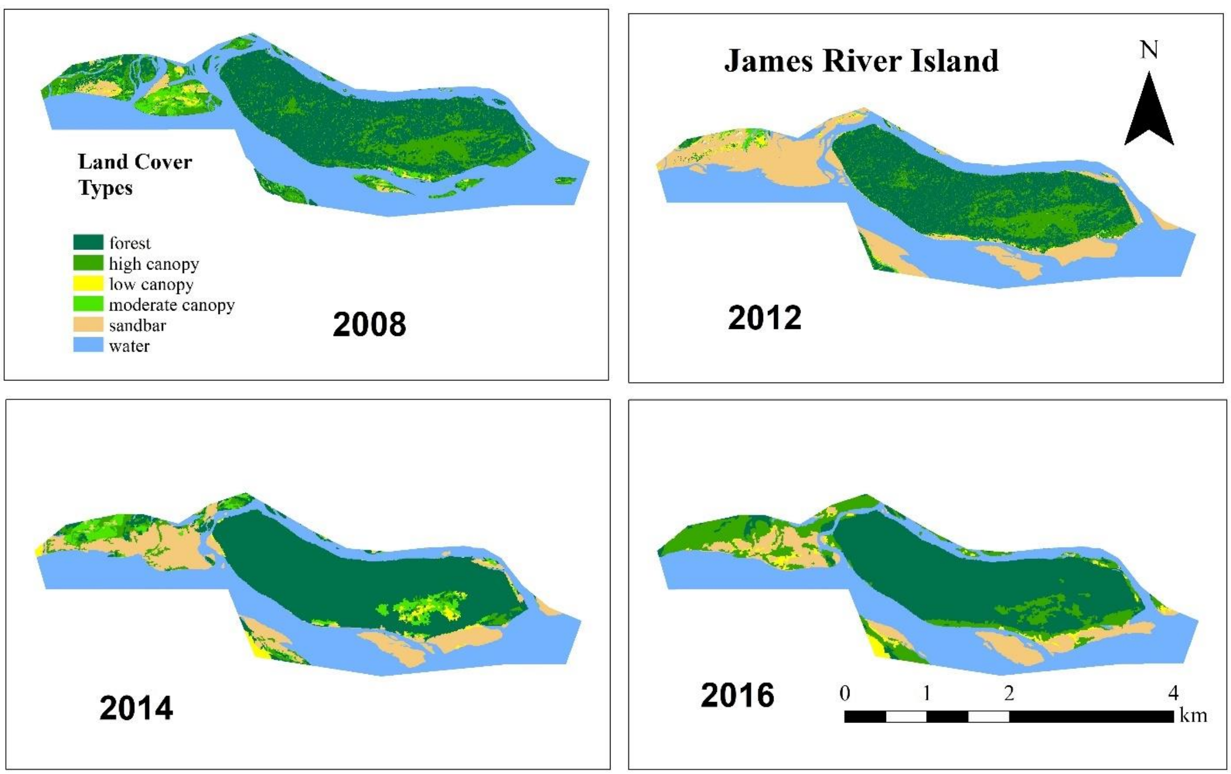


Figure 7: Land cover types change map for James River Island in the 59-mile segment of the MNRR (2008-2016)

Table 6: Raw data showing hectares of change from 2008-2016 landcover change for the James River Island reach.

Category	2008 (ha)	2012 (ha)	2014 (ha)	2016 (ha)
Forest	265.6	220.1	292.8	283.5
High canopy	106.0	78.9	27.1	62.7
Low canopy	10.8	10.4	11.9	14.9
Moderate canopy	28.5	7.2	31.2	49.7
Sandbar	11.2	144.5	106.7	72.9
Water	347.1	310.3	303.1	288.9
Total Area	769.2	771.5	772.8	772.8

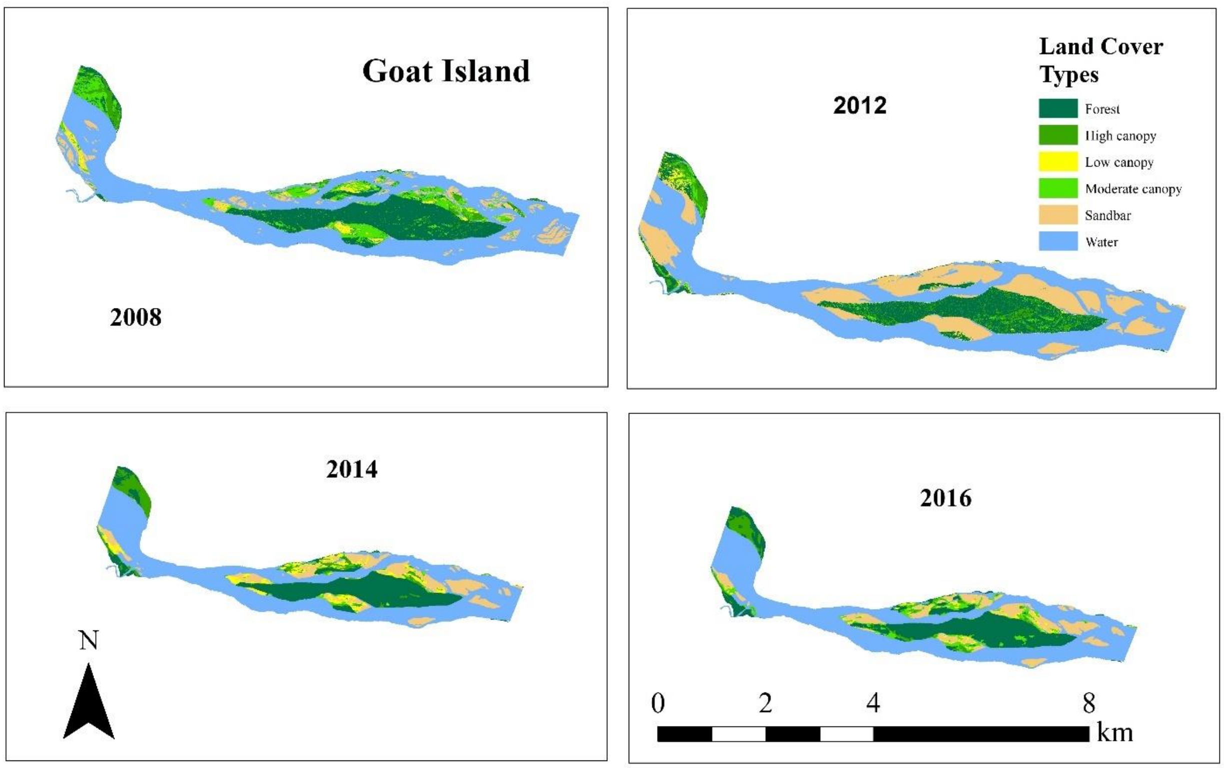


Figure 8: Land cover types change map for Goat Island in the 59-mile segment of the MNRR (2008-2016)

Table 7: Changes in area of different landcover types for 2008-2016 at the Goat Island reach.

Category	2008 (ha)	2012 (ha)	2014 (ha)	2016 (ha)
Forest	250.1	193.9	258.1	264.1
High canopy	87.2	69.9	72.2	48.9
Low canopy	28.2	16.3	59.4	18.5
Moderate canopy	119	23.1	16.7	66.1
Sandbar	89.1	296.1	144.5	146.5
Water	679.5	606.2	656.9	662.3
Total Area	1252.6	1205.6	1207.8	1206.4

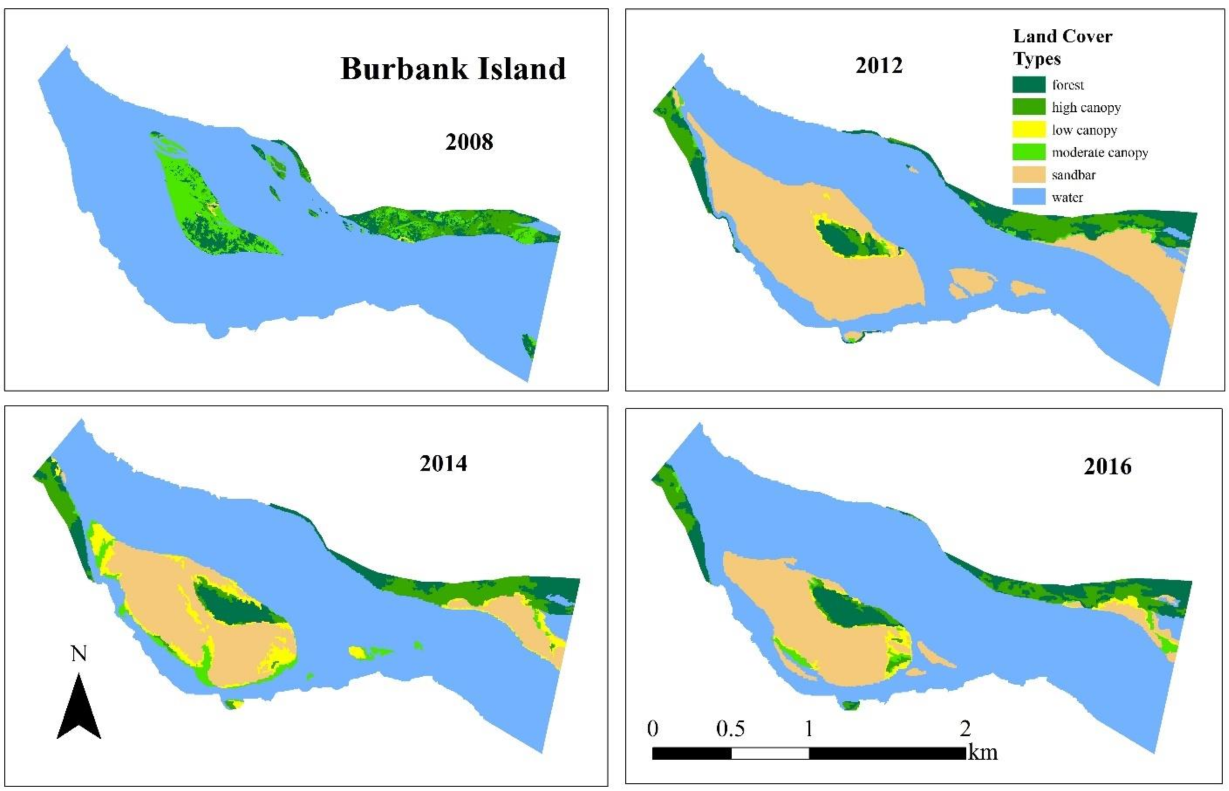


Figure 9: Land cover types change map for Burbank Island in the 59-mile segment of the MNRR (2008-2016)

Table 8: Changes in area of different landcover types for 2008-2016 at the Burbank Island reach.

Category	2008 (ha)	2012 (ha)	2014 (ha)	2016 (ha)
Forest	14.6	21.2	19.4	21.8
High canopy	11.2	18.3	17.2	14.5
Low canopy	0.2	2.0	14.3	4.7
Moderate canopy	18.7	33.8	6.9	3.3
Sandbar	0.1	98.6	54.6	49.9
Water	257.5	179.8	207.1	226.8
Total Area	302.4	353.7	319.7	321.2

3.1.2 Effects of the 2011 flood on sandbar and vegetation area

To examine the impact of 2011 flooding on vegetation patterns and sandbar formation in the two segments of the MNRR, I calculated the total vegetation and sandbar area before (2008) and after (2012, 2014, 2016) the flood event, on each of the seven study reaches. I combined four vegetation categories (forest, high canopy, moderate canopy, and low canopy) to come up with the vegetation total area.

The analysis of the three post-flood year data (2012-2016) shows some interesting trends within the two segments of the MNRR (Table 9). For example, the study reaches in both the 39-mile and 59-mile segments of the MNRR showed a sharp increase in sandbar area (2008-2012) after the 2011 flood; however, sandbar areas in both segments decreased over 2012-2014. For 2016, all three of the 39-mile study reaches showed an increase in the total sandbar area. However, a mixed pattern occurred for the 59-mile reaches as one site (Goat Island) showed a small increase in sandbar area, while the other three sites showed strong (James River Island, 33.8 ha or 32% decline) or small (Green & Sister Island and Burbank Island) decreases in sandbar area from 2014-2016.

Table 9: Total vegetation and sandbar area in the seven study sites between 2008-2016 (area in hectares)

Study Sites	2008 (ha)		2012 (ha)		2014 (ha)		2016 (ha)	
	Veg	Sandbar	Veg	Sandbar	Veg	Sandbar	Veg	Sandbar
Tribal Island	119.4	4.7	99.5	49.5	134.9	20.9	149.9	83.3
Sanctuary Island	269.4	5.9	186.7	148.5	288.9	49.3	288.4	53.1
Niobrara Island	471.2	5.9	304.1	472	398.9	265.3	285.3	365.6
Green & Sister Island	79.2	2.1	45.2	39.9	64.5	30.3	69.4	29.6
James River Island	410.9	11.3	318.1	144.6	363.5	106.7	410.9	72.9
Goat Island	484.5	89.1	303.2	296.1	406.5	144.6	397.4	146.51
Burbank Island	44.78	0.2	41.59	98.76	58.02	54.61	44.54	49.51

Opposite to the patterns of sandbar formation, all the seven study sites in the MNRR experienced a decrease in total vegetation area from before to after the 2011 flood. Niobrara Confluence, James River Island, and Sanctuary Island experienced the highest net declines in vegetated area, while Green and Sister Island had the highest proportional decline from 2008-2012 (43% decline). From 2012-2014, there was a reverse pattern, with an increase in total vegetation area in all seven of the study reaches. Finally, from 2014-2016, three reaches (Tribal, Green, and James) showed increases, two reaches (Sanctuary and Goat) showed small decreases (very little change for Sanctuary), and the remaining two reaches (Niobrara and Burbank) showed somewhat greater decreases in total vegetation area. James River Island has the highest growth in vegetated area (47.4 ha or 13% increase) compared to the other study sites. However, there was a sharp decrease for Niobrara (loss of 113.6 ha or 28% decline) and Burbank Island (loss of 13.5 ha or 23% decline) over 2014-2016. Comparing the two segments of the MNRR, a sharp decline in total vegetation area occurred in both in 2008-2012, followed by a moderate increase in 2012-2014. However, changes in the two segments differed in 2016. Compared to 2014, all sites in the 39-mile segment, except Tribal, experienced a decrease in total vegetation area by 2016. For the 59-mile segment, two sites (Green & Sister and James River Island) showed an increase, while the other two (Goat and Burbank Island) showed an overall decrease in total vegetation area.

The visual analysis of the relationship between sandbar formation and vegetation expansion revealed an inverse relationship. I calculated the proportion of the terrestrial area that was in vegetation or sandbar on each map year within each study reach. In 2008, the sites on both the 39-mile and 59-mile segments were dominated by vegetation (all >80%) (Figure 10). However, an inverse pattern was visible in 2012 as this year has the largest sandbar areas and lowest vegetation areas (Figures 10 and 11). This is likely because of the 2011 flood, which led to both a significant amount of sand deposition and erosion of vegetation. Apart from the Tribal Island and Niobrara Confluence reaches, the proportional area in sandbar coverage decreased gradually, and the proportional vegetation area increased from 2012 to 2016 (Figures 10 and 11).

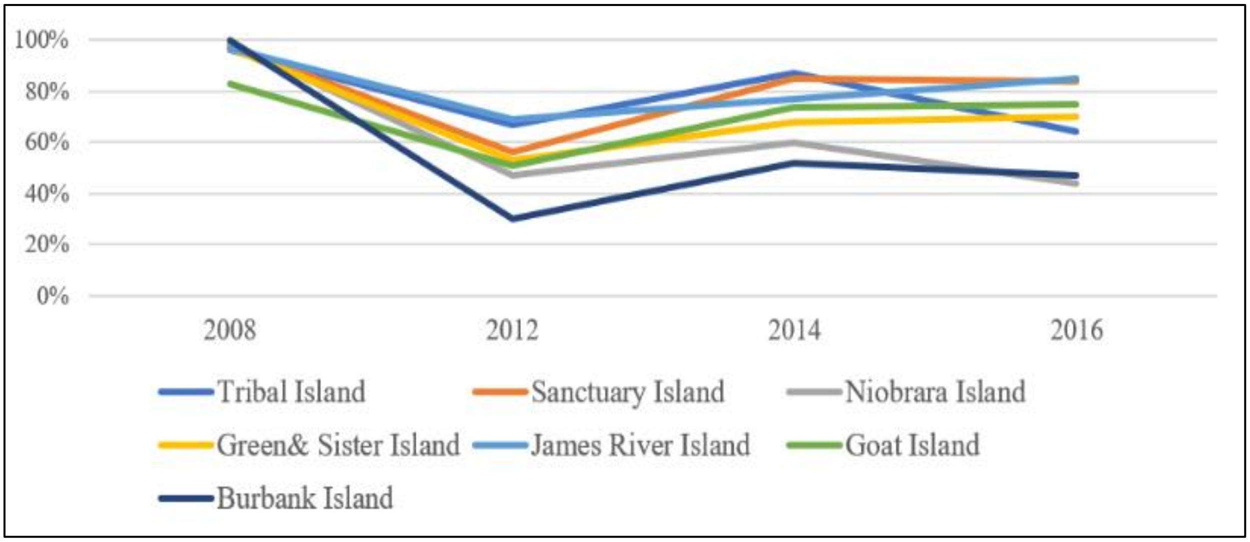


Figure 10: Percentage of the terrestrial area (sandbar plus vegetation) covered by vegetation over the years 2008-2016 for each study reach.

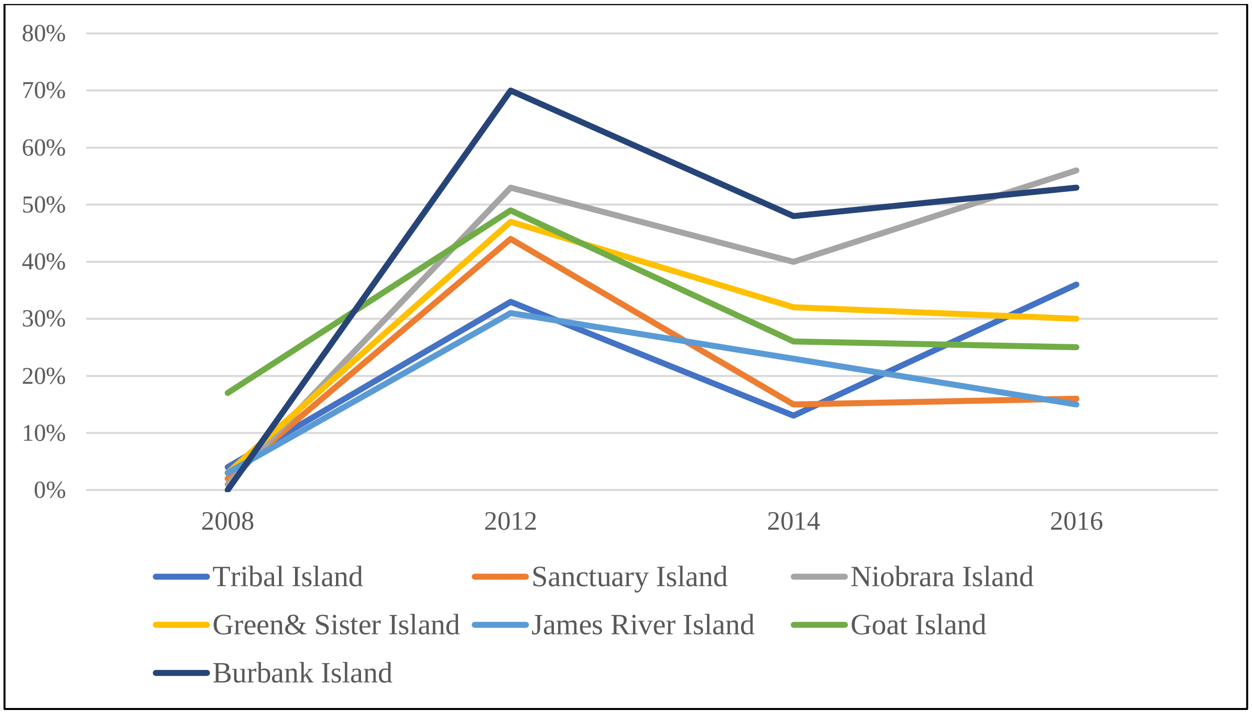
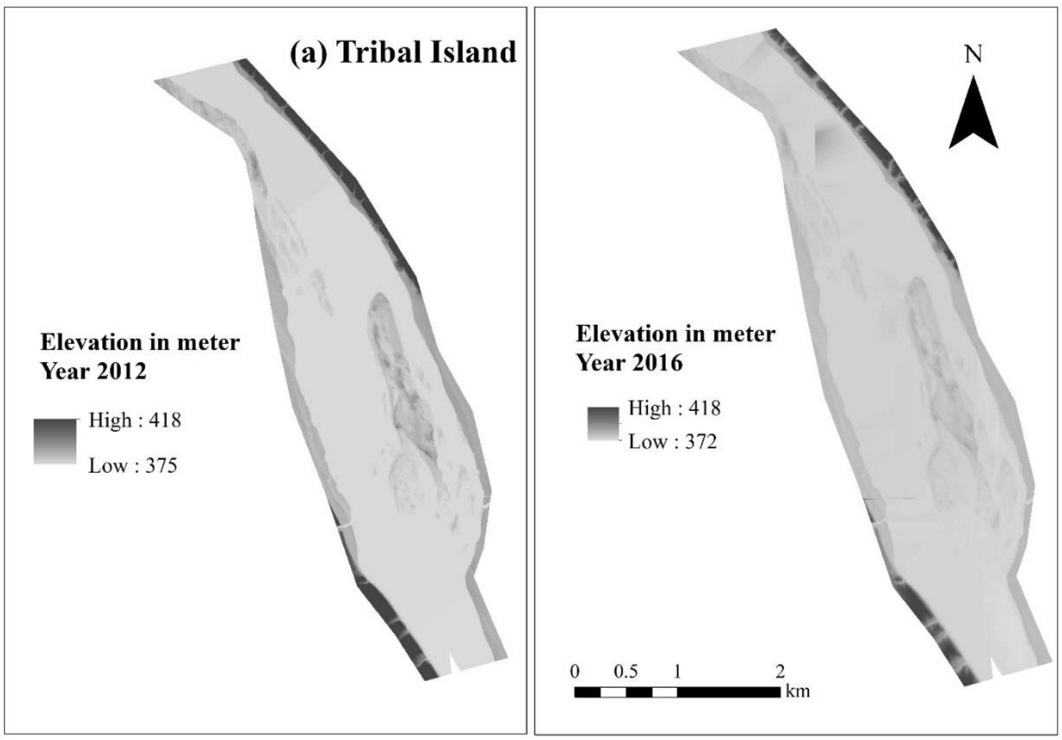


Figure 11: Percentage of the terrestrial area (sandbar plus vegetation) covered by unvegetated sandbar over the years 2008-2016 for each study reach.

3.2 Relationships between Landcover and Sandbar Topography

The DEMs created from LiDAR imagery show some variation in the elevations of the seven study reaches (Figures 12 and 13). Because they are upstream, study sites located in the 39-mile segment have higher upper and lower elevation (428-369 m) compared to study sites located in the 59-mile segment (371-338 m).



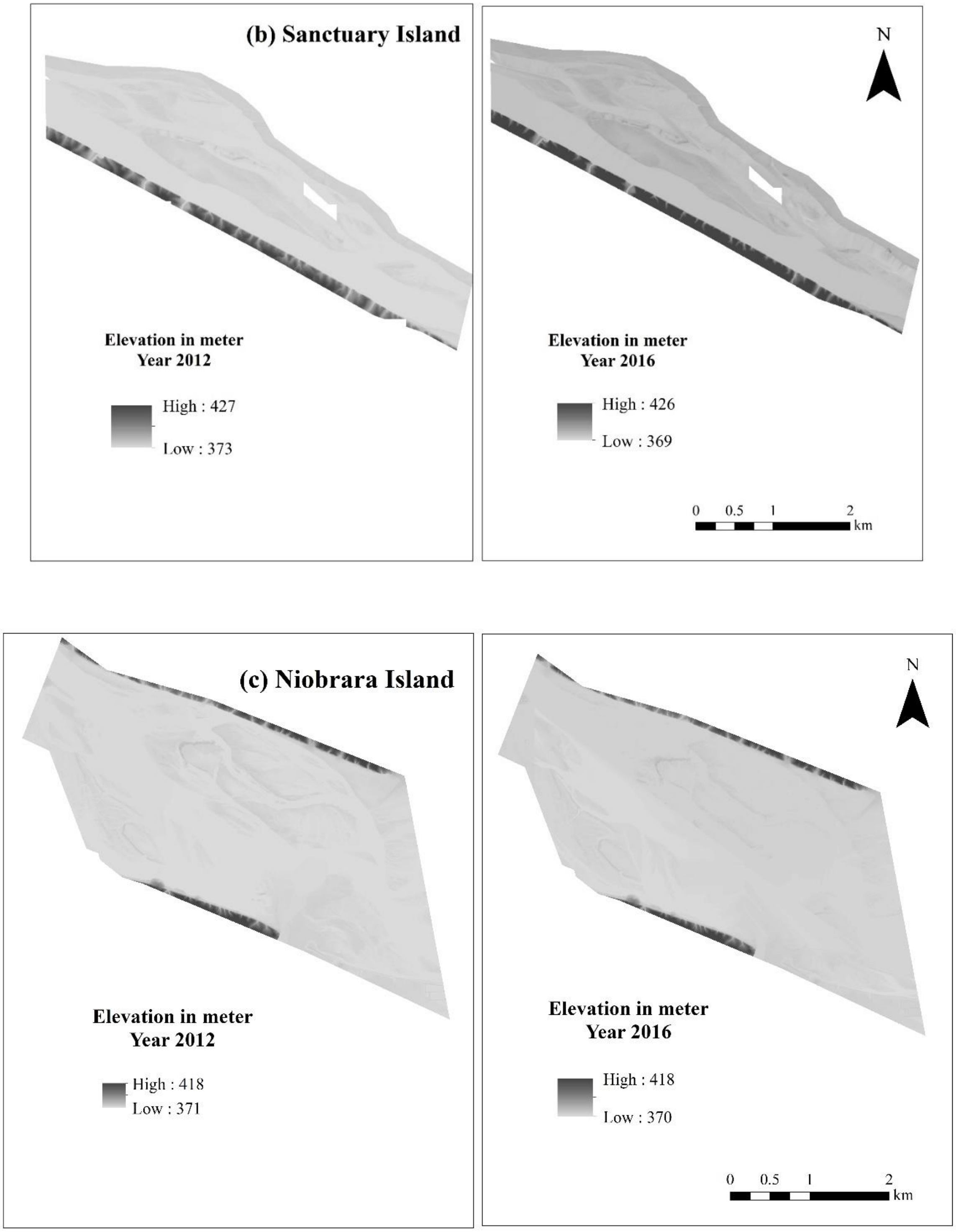
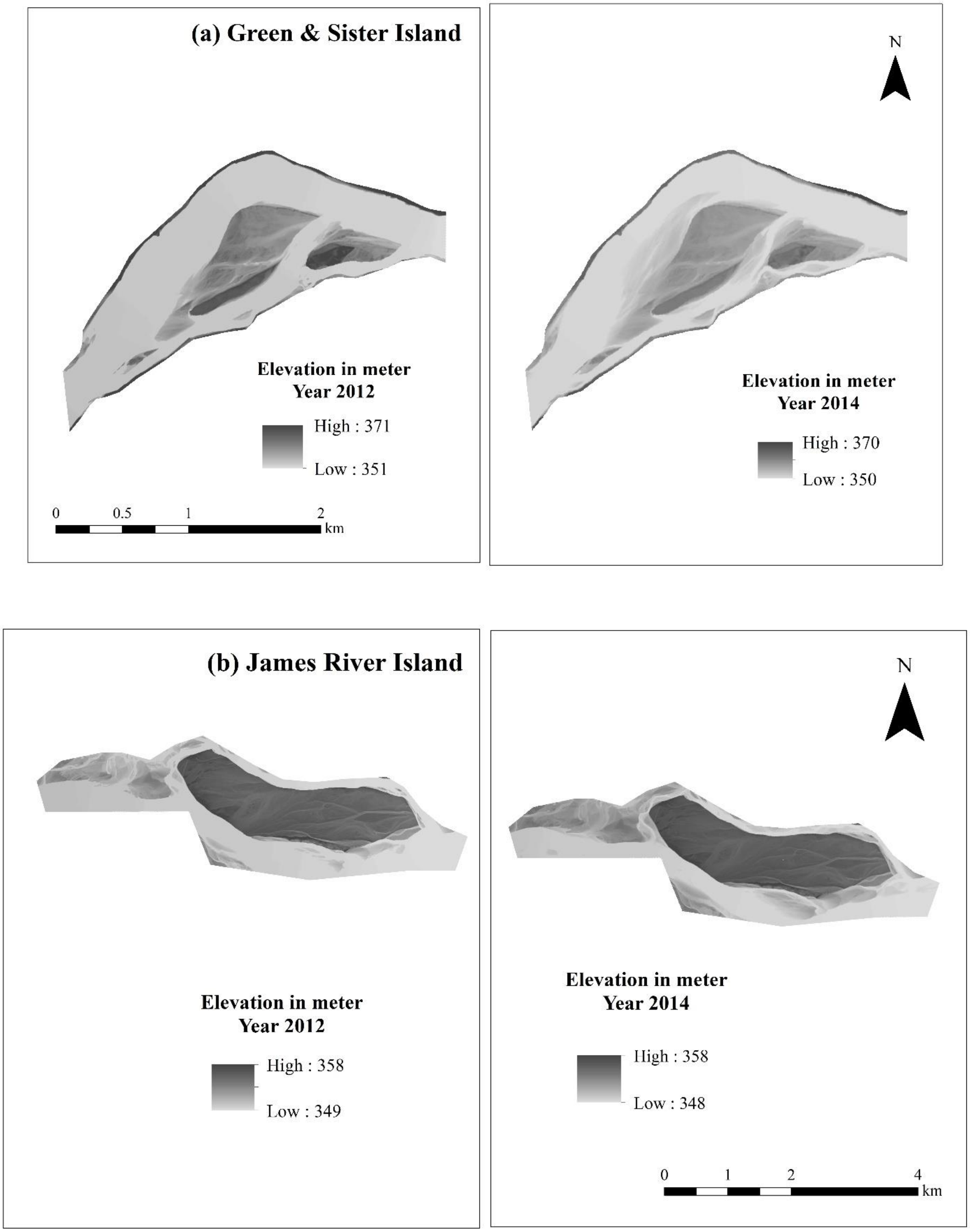


Figure 12: Digital Elevation Models (DEM) for three study sites, (a) Tribal Island, (b) Sanctuary Island, and (c) Niobrara Confluence, in the 39-mile segment (2012-2016)


(a) Green & Sister Island
N
Elevation in meter
Year 2012
High : 371
Low : 351
0
0.5
1
2
km
Elevation in meter
Year 2014
High : 370
Low : 350
(b) James River Island
N
Elevation in meter
Year 2012
High : 358
Low : 349
Elevation in meter
Year 2014
High : 358
Low : 348
0
1
2
4
km

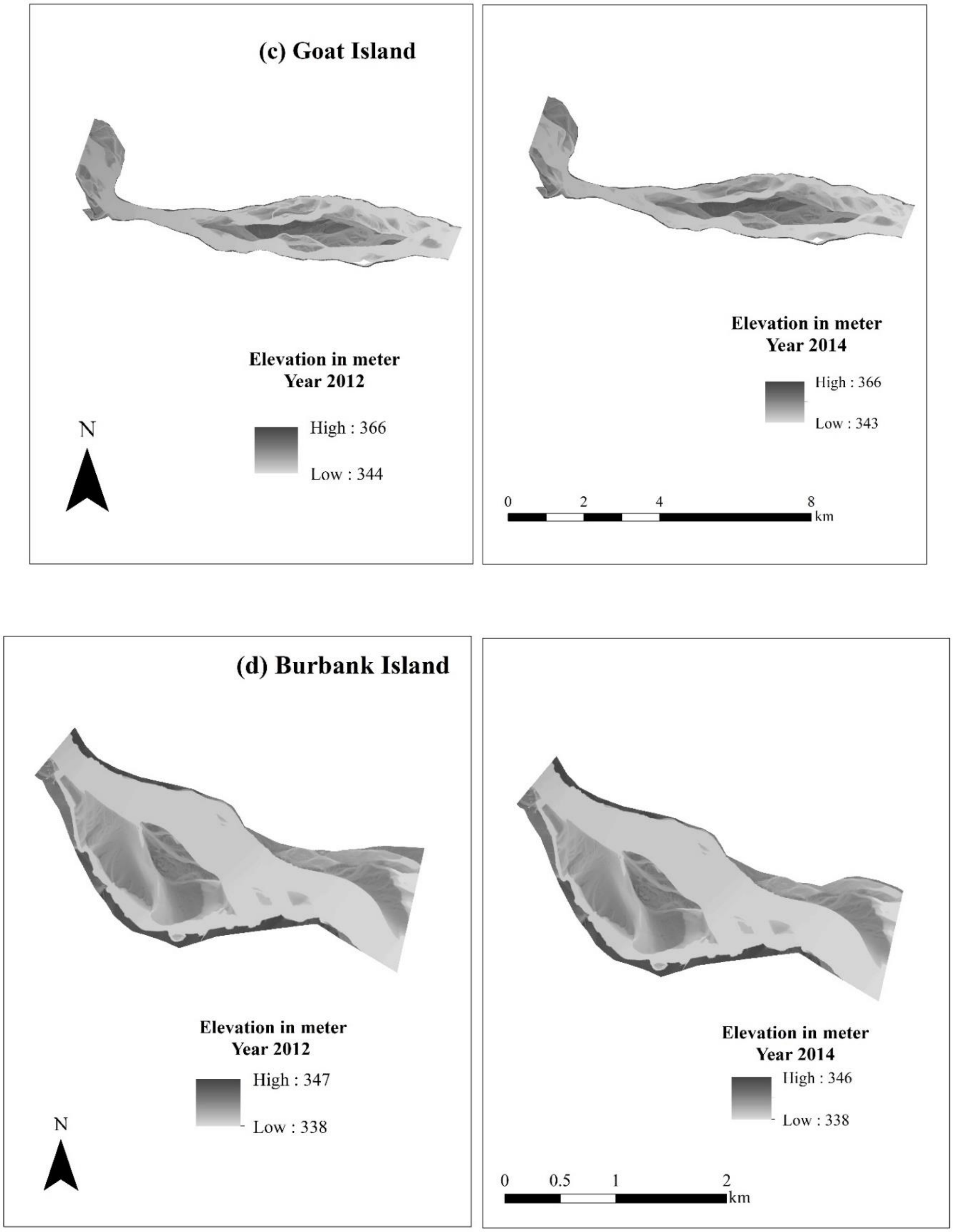


Figure 13: Digital Elevation Models (DEM) for the four study sites (a) Green & Sister Island, (b) James River Island, (c) Goat Island, and (d) Burbank Island in the 59-mile segment (2012-2014).

Although the elevation range offers a useful visualization of the elevation patterns of the study reaches, it is difficult to compare the relationship between elevation and vegetation pattern using overall elevation data. So, I used the relative elevation (elevation above water surface) of the sampling points to explore the relationships between vegetation types and site topography. Relative elevation offers a useful index to compare how likely a site is to be flooded or eroded, how high a surface would be above the river level and water table. I used one-way ANOVA and post hoc analysis to test four hypotheses about differences in relative elevation in 2012 and 2014/2016 across vegetation types and study reaches:

Hypothesis 1 (H1)

Did plots with different vegetation types (high canopy, moderate canopy, low canopy, forest, and sandbar) differ in relative elevation in 2012?

Hypothesis 2 (H2)

Did plots with different vegetation types (high canopy, moderate canopy, low canopy, forest, and sandbar) differ in relative elevation in 2014/2016?

Hypothesis 3 (H3)

Did relative elevation of plots differ among the seven study reaches (Tribal, Sanctuary, Niobrara, Green and Sister, James River, Goat, and Burbank) in 2012?

Hypothesis 4 (H4)

Did relative elevation of plots differ among the seven study reaches in 2014/2016?

3.2.1 Vegetation types and relative plot elevation in 2012

First, I tested the hypothesis (H1) that there were significant differences in relative plot elevations in 2012 among the five vegetation types (high canopy, moderate canopy, low canopy, forest, and sandbar) across the study reaches. One-way ANOVA resulted in a significant p-value ($F_{5, 207}$ =13.85, $p < 0.00001$), suggesting that there were differences in relative elevation among vegetation types. The value of the R-squared statistic was 0.22. So, 78% of the variation in relative elevations among plots was not accounted for by vegetation type. Post-hoc Tukey's multiple comparisons tests (Table 10) indicate that forest and low canopy did not differ significantly from each other in 2012 relative plot elevation but had significantly higher plot elevations than the other three categories. These three other types - high canopy, moderate canopy, and sandbar - did not differ significantly from each other.

Table 10: Summary of pairwise comparisons of relative elevation (plot elevation – mean water surface elevation in 2012) differences among original vegetation types in the year 2012. Different letter superscripts indicate significant (p<0.05) differences in mean elevation between the vegetation types; those sharing the same letter are not significantly different.

Vegetation Type (year 2012)	n	Mean relative elevation (m)	Standard Deviation (m)
forest	34	2.21[a]	0.95
high canopy	27	0.86[b]	0.91
low canopy	18	1.99[a]	0.86
moderate canopy	10	1.04[b]	0.77
sandbar	118	1.26[b]	0.77
Total	207	1.42	0.93

3.2.2 Vegetation types and relative elevation in 2014/2016

I also tested the hypothesis (H2) that there were significant differences in relative plot elevations in 2014/2016 among the five vegetation types (high canopy, moderate canopy, low canopy, forest, and sandbar) across study reaches. One-way ANOVA resulted in a significant p-value ($F_{5, 207}$ =6.95, $p < 0.00001$), suggesting that there were differences in relative elevation among vegetation types. The value of R-squared was 0.14, which means that 86% of the variation in relative elevation among plots in 2014/2016 was not accounted for by vegetation type in 2016.

Table 11: Summary of pairwise comparisons of relative elevation (plot elevation – mean water surface elevation in 2012) differences among original vegetation type in the year 2014/2016. Different letter superscripts indicate significant (p<0.05) differences in mean elevation between the vegetation types; those sharing the same letter are not significantly different.

Vegetation Type (year 2016)	n	Mean relative elevation (m)	Standard Deviation (m)
forest	28	2.04^{a}	1.22
high canopy	60	1.49^{ac}	0.97
low canopy	24	1.31^{c}	0.79
moderate canopy	35	1.65^{ac}	0.83
sandbar	60	0.96^{b}	0.69
Total	207	1.42	0.93

As with the 2012 plot elevations, the analysis indicates that the forest generally had higher relative elevation values than other vegetation types in 2016. Post-hoc Tukey's multiple comparisons tests (Table 11) indicate that the mean relative elevation of forest plots was significantly greater than both sandbar and low canopy. Mean relative elevation of sandbar plots was also significantly lower than all other vegetation categories. However, high, moderate, and low canopy cover plots did not significantly differ from each other in mean relative plot elevation in 2014/2016.

3.2.3 Study sites and relative elevation of the year 2012

I also compared patterns of relative plot elevation for the year 2012 among the seven study reaches (H3). One-way ANOVA resulted in a significant p-value ($F_{6, 206} = 11.72$, $p < 0.00001$), suggesting that there were significant differences in mean relative plot elevation among study reaches. The value of R-squared was 0.25, which means that study sites did not account for 75% of the variation in relative elevation among plots in 2012.

Table 12: Summary of pairwise comparisons of relative elevation (plot elevation – mean water surface elevation in 2012) differences among study sites in 2012. Different letter superscripts indicate significant (p<0.05) differences in mean elevation between the vegetation types; those sharing the same letter are not significantly different

Study Site	n	Mean relative elevation (m)	Standard Deviation (m)
Burbank	29	1.91^{a}	1.02
Goat Island	46	1.46^{a}	0.74
Green & Sister	26	1.20^{a}	0.95
James River	26	1.80^{a}	0.68
Niobrara	35	0.81^{b}	0.61
Sanctuary	28	0.94^{ab}	0.92
Tribal	23	0.80^{b}	0.90
Total	213	1.38	0.94

In general, study reaches on the 59-mile segment had substantially greater relative plot elevations than those on the 39-mile segment (Table 12). Post-hoc Tukey's multiple comparisons showed that the mean relative plot elevation for the four reaches on the 59-mile segment did not differ significantly from each other but were significantly greater than two of the three reaches (Niobrara Confluence and Tribal Island) on the 39-mile segment (Table 12). Only Sanctuary Island did not differ significantly in mean elevation from the four 59-mile segment reaches. As with the 59-mile segment, locations in the 39-mile segment do not differ significantly in relative elevation from each other.

3.2.4 Study sites and relative elevation of the year 2014/2016

I also compared patterns of relative plot elevation of the year 2014/2016 among the seven study reaches (H4). As with the 2012 elevation comparisons, one-way ANOVA resulted in a significant p-value ($F_{6, 206}$ =17.26, $p < 0.00001$). However, the value of R-squared was relatively low (0.33), which means that study sites did not account for 67% of the variation in relative elevation among plots in 2014/2016.

Table 13: Summary of pairwise comparisons of relative elevation (plot elevation – mean water surface elevation in 2012) differences among study sites, based on 2014/2016 LiDAR. Different letter superscripts indicate significant (p<0.05) differences in mean elevation between the vegetation types; those sharing the same letter are not significantly different.

Study Site	n	Mean relative elevation (m)	Standard Deviation (m)
Burbank	29	2.16^{a}	1.04
Goat Island	46	1.43^{b}	0.76
Green & Sister	26	1.94^{ab}	0.92
James River	26	$1.90^{a\ b}$	0.62
Niobrara	35	0.79^{c}	0.40
Sanctuary	28	0.65^{c}	0.99
Tribal	23	0.78^{c}	0.89
Total	213	1.37	0.98

Based on post-hoc Tukey's multiple comparisons, we see that Burbank plots had a significantly higher mean relative elevation than those at Goat Island but were not different from those on James or Green, and that Goat does not differ significantly from James or Green either (Table 13). We also see that relative plot elevations at the three sites on the 39-mile segment do not differ from each other significantly, but all are significantly lower than any of the sites on the 59-mile segment.

3.3 Relationships among Topographic, Geomorphic, and Landcover Changes

3.3.1 Analysis of landcover change categories for 39-mile and 59-mile segments.

The analysis of sandbar and vegetation coverage revealed that 2011 flood events significantly affected both segments. A sharp increase in total sandbar area and a decrease in vegetation area were visible in both the 39-mile and 59-mile segments from 2008-2012. However, these area totals do not indicate how the topography and geomorphological changes affected initial sandbar formation and subsequent vegetation changes within the study reaches. Below, I discuss how topography affected the sandbar and vegetation coverages between 2012-2016.

For the 39-mile segment, I used 2012-2016 LiDAR and changes in vegetation cover types between 2012 and 2016 to analyze the effect of topography on the formation of sandbar and vegetation coverage. I prepared an elevation change map (with erosion and deposition) and then visually analyzed the map with respect to a landcover change map. In the landcover change map, I had categories of vegetation transitions (conversions) from 2012 to 2016, like sandbar-vegetation, vegetation-sandbar, and others. The sandbar-vegetation category means an area that was sandbar in 2012 had changed to vegetation by 2016. Similarly, vegetation-sandbar means that an area of vegetation in 2012 changed to sandbar area in 2016. Unfortunately, 2016 LiDAR was not available for the 59-mile segment. So, instead of 2016, I used 2014 LiDAR and performed elevation and landcover changes between 2012 and 2014 for the four sites in the 59-mile segment.

Table 14: Raw data showing areas (in ha) of landcover conversion from 2012-2016 for study reaches on the 39-mile segment.

Conversion	Tribal Island (ha)	Sanctuary Island (ha)	Niobrara Confluence (ha)
Water-sandbar	73.11	6.22	46.79
Water-vegetation	14.91	10.02	14.38
Sandbar-sandbar	8.64	38.03	144.54
Sandbar-vegetation	37.79	100.95	163.33
Sandbar-water	2.59	8.90	35.44
Vegetation-sandbar	1.28	8.73	172.67
Vegetation-vegetation	96.19	170.56	104.96
Vegetation-water	0.55	1.80	20.35

In addition to visualization of changes, I also calculated the areas of different categories of landcover conversion (see Tables 14 and 15). I mainly focused on two broad types of change: new vegetation (water-vegetation and sandbar-vegetation) and lost vegetation (vegetation-sandbar, vegetation-water). In the 39-mile segment, the areas of new vegetation for Tribal, Sanctuary, and Niobrara were 52.27, 110.97, and 177.71 ha, and the areas of lost vegetation were 1.83, 10.53, and 193.02 ha, respectively (Table 14). Based on these numbers, both Tribal and Sanctuary Island showed a net gain in vegetation area in 2016, while Niobrara experienced a net loss of vegetation area.

In the 59-mile segment, the areas of new vegetation formed from 2012-2014 for Green & Sister, James, Goat, and Burbank Island were 20.49 ha, 46.96 ha, 106.4 ha, and 21.5 ha; while the total areas of lost vegetation for these four reaches were 0.50, 1.96, 3.27, and 4.17 ha, respectively (Table 15). So, all study reaches in 59-mile segment gained a higher amount of new vegetation than lost vegetation from 2012 to 2014.

Table 15: Raw data showing areas (in ha) of landcover conversion from 2012-2014 for study reaches on the 59-mile segment.

Conversion	Green & Sister Island (ha)	James River Island (ha)	Goat Island (ha)	Burbank Island (ha)
Water-sandbar	7.10	7.87	26.36	0.20
Water-vegetation	4.18	7.32	5.36	1.54
Sandbar-sandbar	22.66	97.57	118.01	54.08
Sandbar-vegetation	16.31	39.64	101.04	19.96
Sandbar-water	0.75	7.32	76.73	24.72
Vegetation-sandbar	0.43	1.24	0.11	0.32
Vegetation-vegetation	43.22	316.03	298.93	36.51
Vegetation-water	0.07	0.72	3.16	3.85

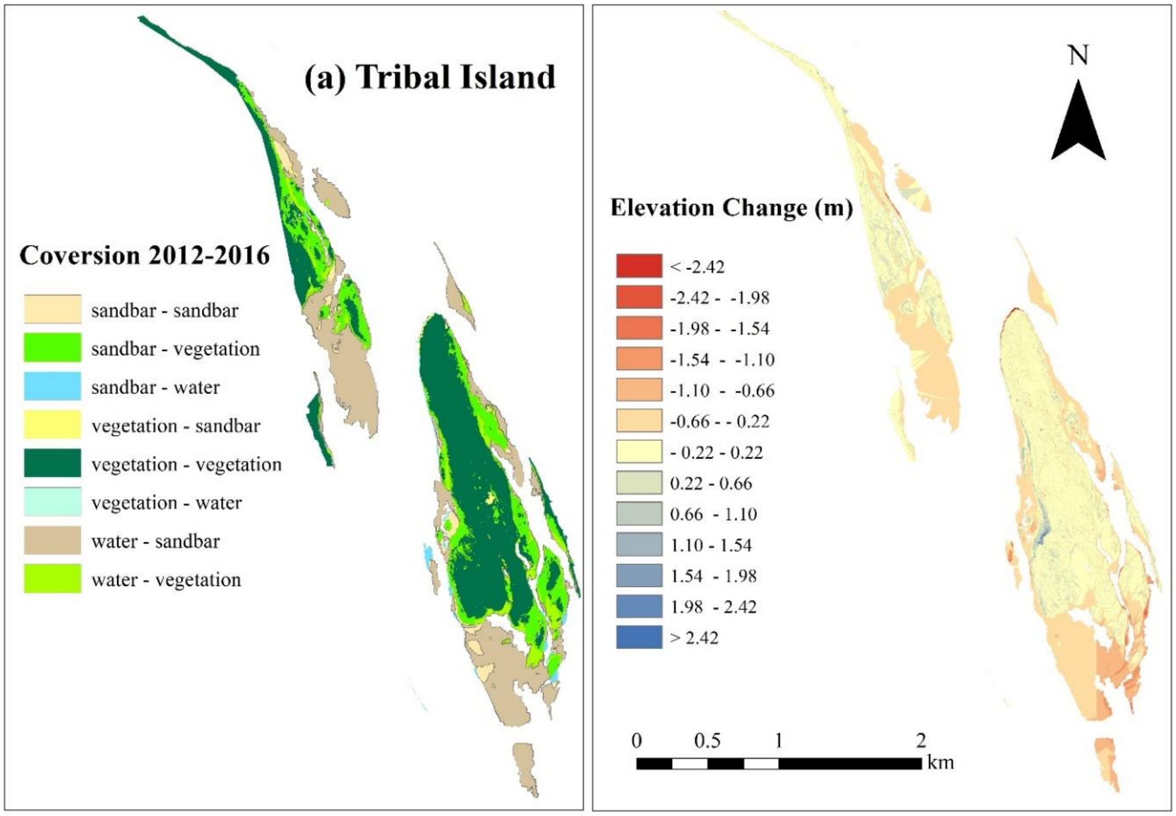
I also found an inverse relationship between vegetation expansion and sandbar formation. For example, based on the transition data from 2012-2016 (Table 14) across the study reaches in the 39-mile segment, 4.9 ha of sandbar area was lost due to erosion (conversion from sandbar to water), while 302.1 ha was lost due to vegetation expansion (conversion from sandbar to vegetation). In the 59-mile segment reaches from 2012-2014 (Table 15), 109.52 ha of sandbar area was lost due to erosion, while 176.95 ha was lost due to vegetation expansion. The data showed a contrast between the two segments. Sandbar losses were almost completely due to vegetation expansion on the 39-mile segment but were due almost as much to erosion as to vegetation expansion on the 59-mile segment. In both cases, there were greater amounts of sandbar area decline from vegetation expansion than from erosion.

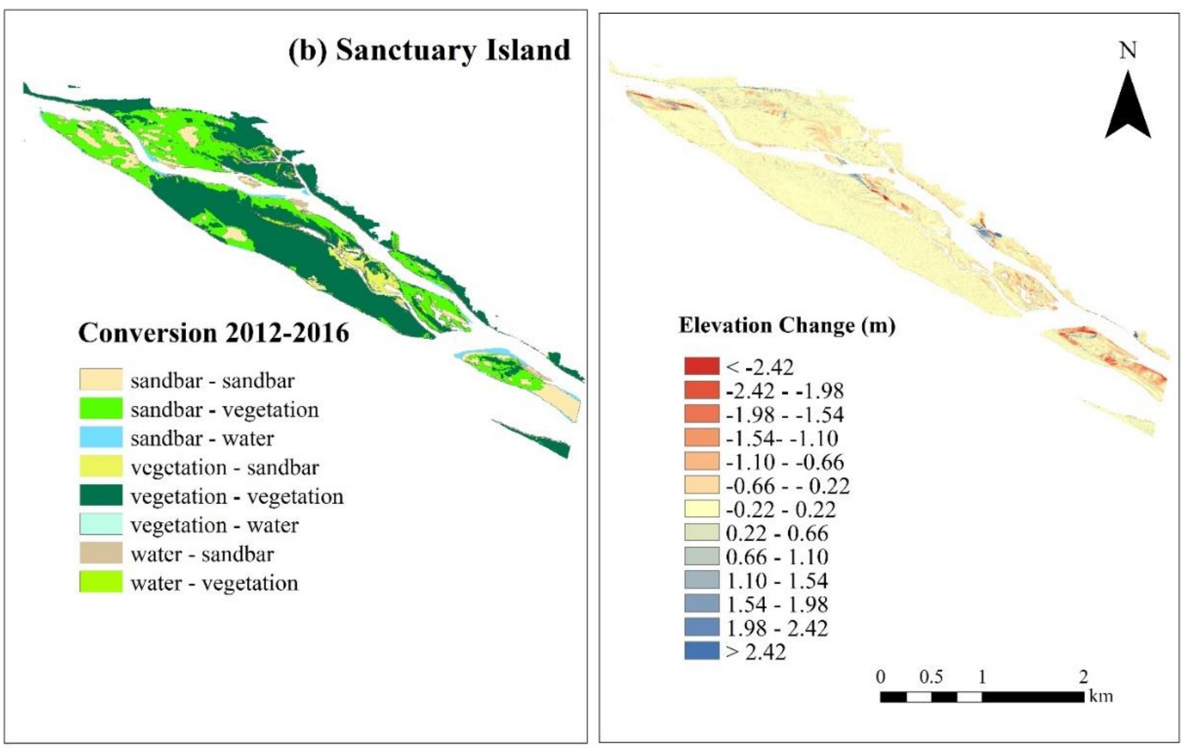
3.3.2 Analysis of the relationship of geomorphology and topography

3.3.2.1 Visual interpretation of maps

In the previous section, I discussed the land cover changes in the seven study reaches of the 39-mile and 59-mile segments. This section will highlight how the topography, such as elevation changes, might affect (or be affected by) the pattern of vegetation changes in the study sites. I conceptualized erosion as a decrease in the sandbar area and deposition as an increase in the total sandbar area at the study sites. However, it may be possible for deposition to occur that results in an increase in the elevation of a surface but does not represent an increase in the area; similarly, erosion may cause a decrease in elevation on a surface without a loss of area. Comparing patterns of erosion vs. deposition with changes in landcover type can help us visualize how vegetation transitions were related to elevation and topographic variation within the study reaches.

Figures 14 and 15 show patterns of erosion and deposition and changes in landcover categories in the 39-mile and 59-mile segments. Both sets of maps show some patterns relating vegetation changes to elevation changes. For example, the northeast corner of the Niobrara Confluence reach (Figure 14c) experienced areas of deposition ranging from <0.22 to 1.54 m, between 2012 and 2016. In that area, the dominant landcover change category was the conversion from sandbar to vegetation, which means those areas contained new, early successional vegetation. On Burbank Island (Figure 15d) some interesting fluvial and eolian changes occurred between 2012 and 2014. For example, the channel (flowing from north to south) created by fluvial processes in the middle of the island had almost disappeared by 2014 (for details, see Figure 13d above). From the 'landcover & elevation change maps,' we can see dune formation, indicated by the purplish color schemes (ranging from 0.22 to 1.54 m). The reddish color schemes indicate erosion (negative elevation change). On the elevation change map at Burbank Island, the mainland bank shows deep red indicating erosion (ranging from < -2.42 to -1.98 m), which corresponds to the 'vegetation-water' category on the vegetation change map (Figure 15d).


(a) Tribal Island
Coversion 2012-2016
sandbar - sandbar
sandbar - vegetation
sandbar - water
vegetation - sandbar
vegetation - vegetation
vegetation - water
water - sandbar
water - vegetation
N
Elevation Change (m)
< -2.42
-2.42 - -1.98
-1.98 - -1.54
-1.54 - -1.10
-1.10 - -0.66
-0.66 - - 0.22
- 0.22 - 0.22
0.22 - 0.66
0.66 - 1.10
1.10 - 1.54
1.54 - 1.98
1.98 - 2.42
> 2.42
0 0.5 1 2
km


(b) Sanctuary Island
Conversion 2012-2016
sandbar - sandbar
sandbar - vegetation
sandbar - water
vegetation - sandbar
vegetation - vegetation
vegetation - water
water - sandbar
water - vegetation
N
Elevation Change (m)
< -2.42
-2.42 - -1.98
-1.98 - -1.54
-1.54- -1.10
-1.10 - -0.66
-0.66 - - 0.22
-0.22 - 0.22
0.22 - 0.66
0.66 - 1.10
1.10 - 1.54
1.54 - 1.98
1.98 - 2.42
> 2.42
0 0.5 1 2
km

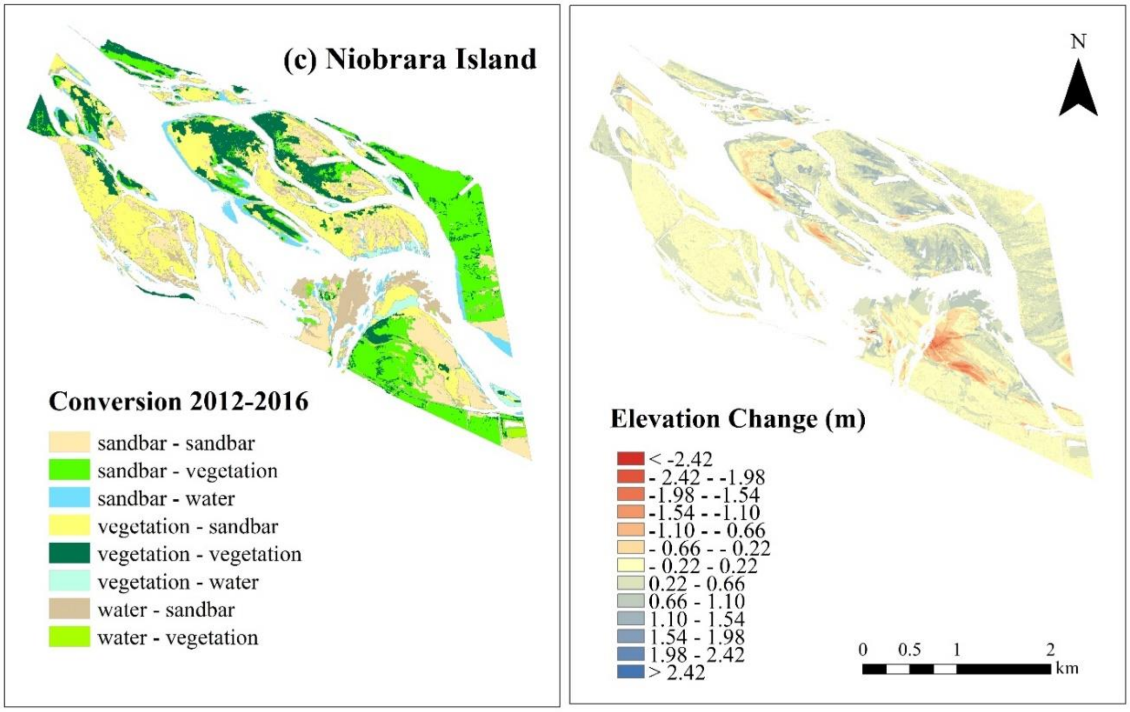
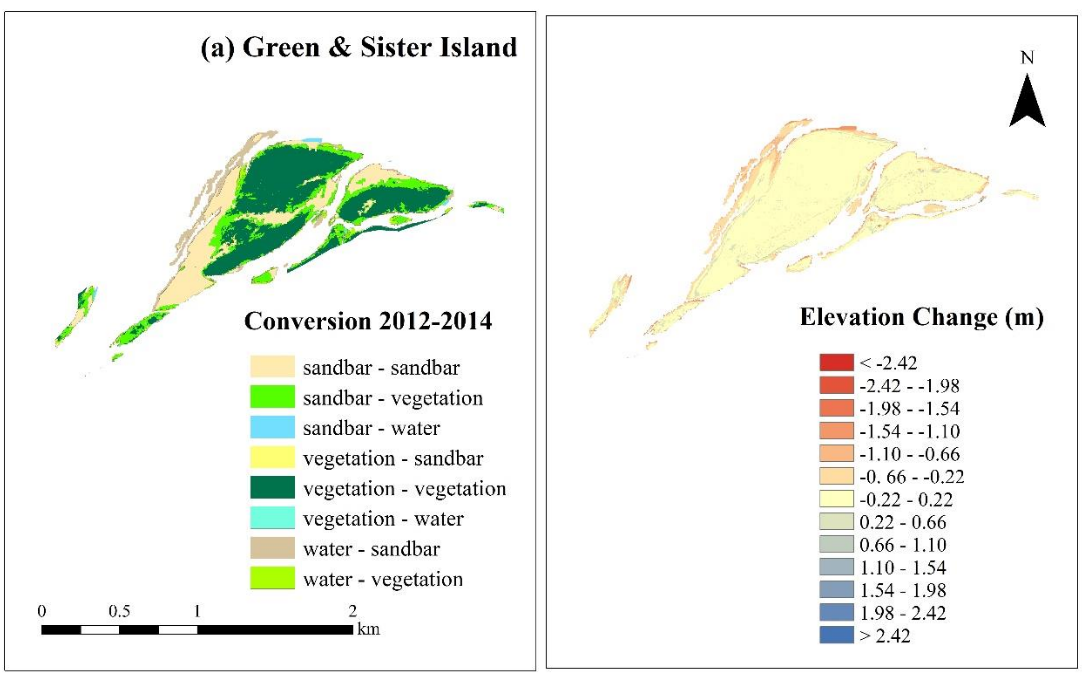
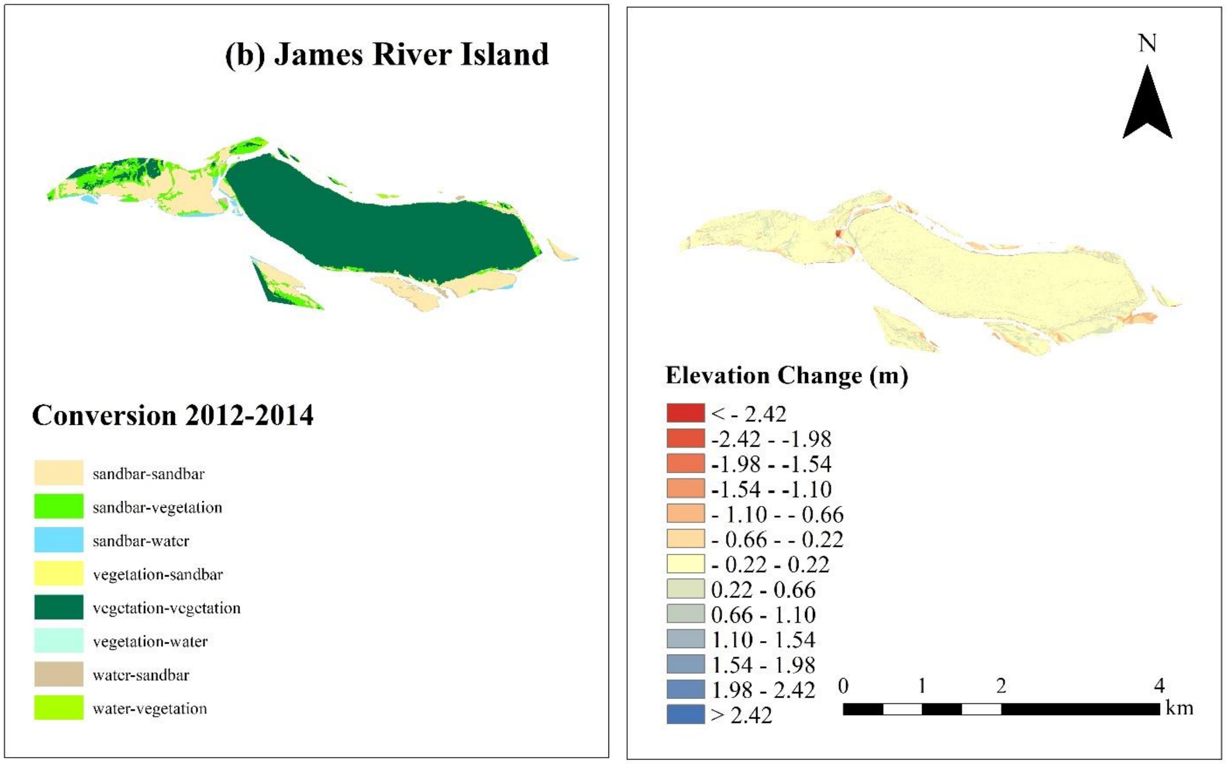
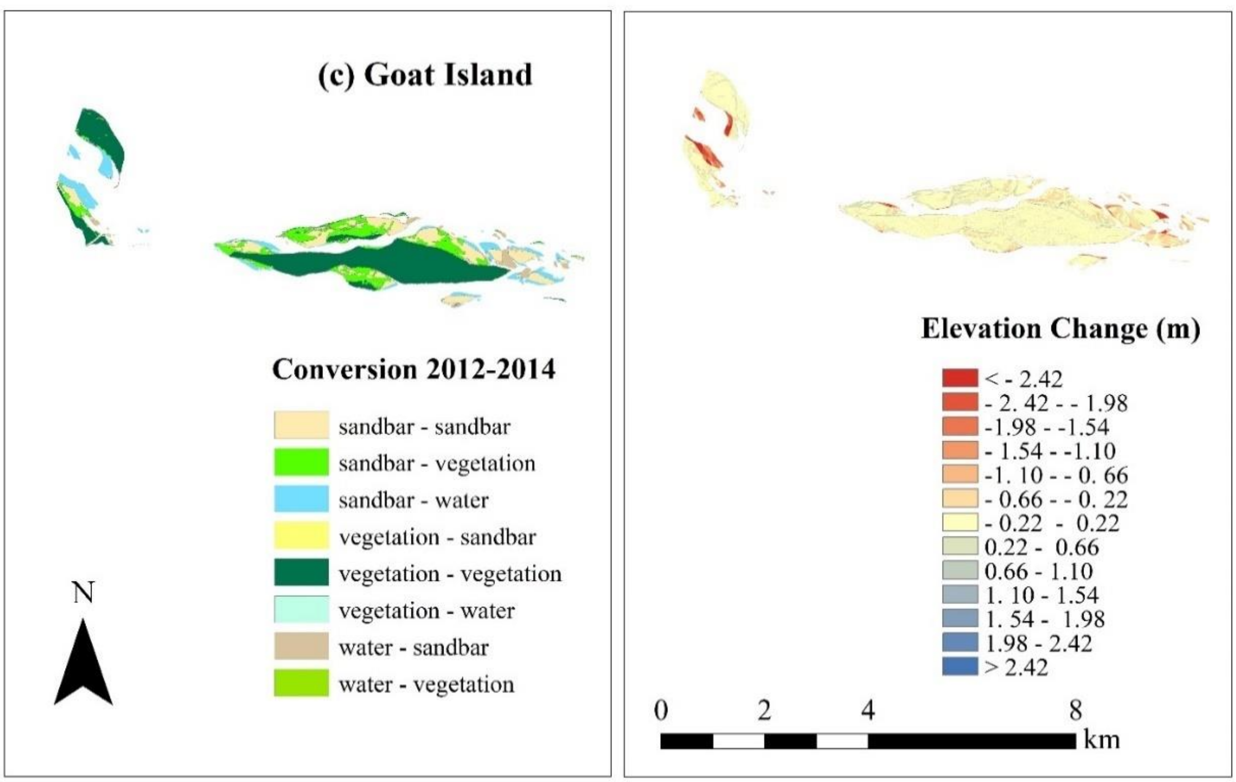


Figure 14: Pattern of erosion and deposition (left) and changes in landcover categories (right) between 2012-2016 for (a) Tribal, (b) Sanctuary, and (c) Niobrara on the 39-mile segment (areas that remained water on both dates were excluded).




(b) James River Island
Conversion 2012-2014
sandbar-sandbar
sandbar-vegetation
sandbar-water
vegetation-sandbar
vegetation-vegetation
vegetation-water
water-sandbar
water-vegetation
N
Elevation Change (m)
< - 2.42
-2.42 - -1.98
-1.98 - -1.54
-1.54 - -1.10
- 1.10 - - 0.66
- 0.66 - - 0.22
- 0.22 - 0.22
0.22 - 0.66
0.66 - 1.10
1.10 - 1.54
1.54 - 1.98
1.98 - 2.42
> 2.42
0 1 2 4
km


(c) Goat Island
Conversion 2012-2014
sandbar - sandbar
sandbar - vegetation
sandbar - water
vegetation - sandbar
vegetation - vegetation
vegetation - water
water - sandbar
water - vegetation
N
Elevation Change (m)
< - 2.42
- 2. 42 - - 1.98
-1.98 - -1.54
- 1.54 - -1.10
-1. 10 - - 0. 66
- 0.66 - - 0. 22
- 0.22 - 0.22
0.22 - 0.66
0.66 - 1.10
1. 10 - 1.54
1. 54 - 1.98
1.98 - 2.42
> 2.42
0 2 4 8
km

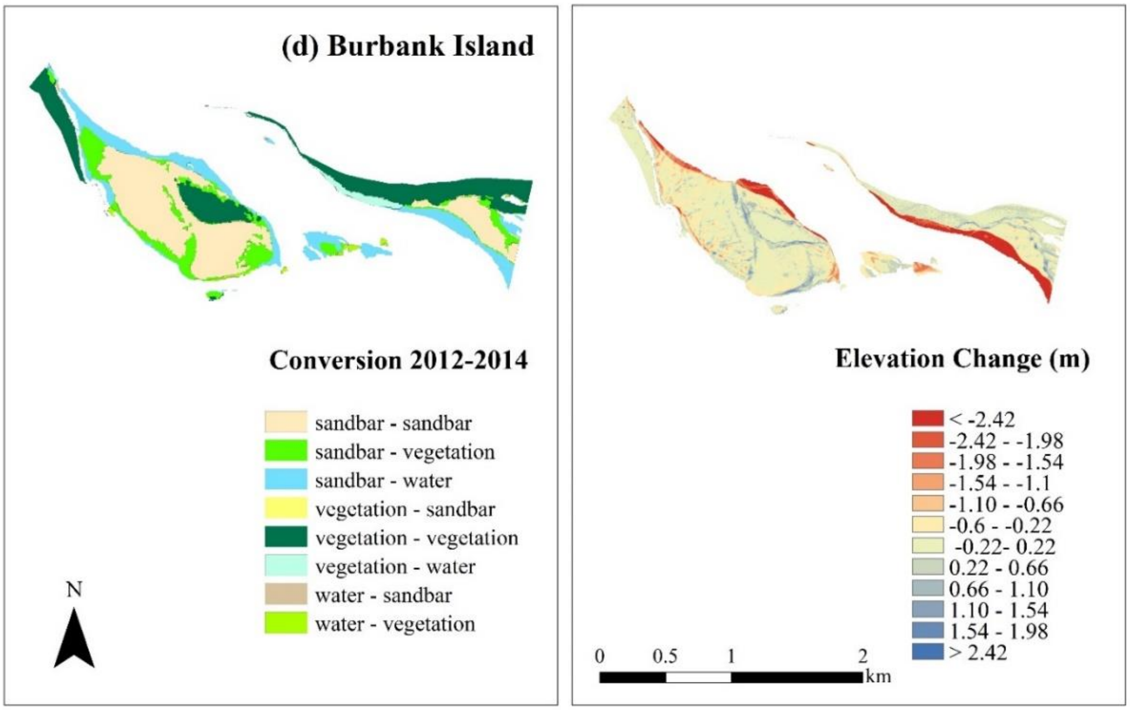


Figure 15: Pattern of erosion and deposition (left) and changes in landcover categories (right) between 2012-2014 for (a) Green & Sister Island, (b) James River Island, (c) Goat Island, and (d) Burbank Island of the 59-mile segment (areas that remained water on both dates were excluded).

3.3.2.2 Quantitative analysis of topographic change and vegetation type

To analyze the relationships among vegetation changes, topography, and geomorphology, I also evaluated patterns of erosion and deposition at the vegetation sampling plot locations mentioned previously. At these sampling points, I used one-way ANOVA and post hoc analysis to examine the relationships between vegetation conversion types (new vegetation, remain sandbar, remain vegetation, and lost vegetation) and elevation change (erosion and deposition) from 2012-2014/2016.

One-way ANOVA resulted in a significant p-value ($F_{3, 209}$ =32.42, $p < 0.00094$), suggesting that mean elevation changes for 2012-2014/2016 differed among the four vegetation change types. The value of R-squared was rather low at 0.07, meaning that the vegetation change type did not account for 93% of the variation in elevation change between dates. The analysis also indicates that plots that remained vegetated between dates generally had positive elevation change values, indicating a tendency towards deposition (Table 16). In contrast, the lost vegetation and remain sandbar points tended to have negative values, suggesting net erosion. Post-hoc Tukey's multiple comparisons tests showed that mean elevation changes at 'remain vegetation' points significantly differed from that at 'lost vegetation' and 'remain sandbar' points (Table 16). Remain vegetation points did not differ significantly in mean elevation change from the new vegetation category, which had a mean elevation change near zero. However, the lost vegetation, new vegetation, and remain sandbar points did not differ significantly in mean elevation change from each other.

Table 16: Summary of pairwise comparisons of mean elevation changes between dates for different vegetation change types. Different letter superscripts indicate significant ($p<0.05$) differences.

Vegetation change type from the year 2012 to 2014/2016	n	Mean elevation change (m)	Standard Deviation (m)
Remain vegetation	67	0.12^{a}	0.24
Lost vegetation	16	-0.25^{b}	0.67
New vegetation	84	-0.01^{ab}	0.41
Remain sandbar	46	-0.12^{b}	0.42
Total	213		

3.4 Vegetation composition and structure on unmanaged vegetated sandbars within the Missouri National Recreational River

3.4.1 Dominant tree and shrub species

Cottonwood was the most frequent tree species, followed by Russian olive, among the species sampled across the seven sandbar reaches in 2020 (Figures 16). At the Niobrara Confluence site, however, we did not sample any trees except for four yellow willows (*Salix lutea*). Yellow willow was also the dominant tree species on the Sanctuary Island plots. Burbank had the largest number of tree species among the seven sites. There I found almost all of the tree species we sampled - cottonwood, Russian olive, eastern red cedar, green ash (*Fraxinus pennsylvanica*), peachleaf willow (*Salix amygdaloides*), and yellow willow. Other tree species sampled across some of the reaches included white mulberry (*Morus alba*) and American (*Ulmus americana*) and Siberian elms.

Sandbar willow (*Salix interior*) was the most abundant shrub species at five sites, including more than 90% of the shrub/sapling stems on the Tribal Island and Niobrara Confluence reaches (Figure 17). On Sanctuary Island, in contrast, cottonwood saplings composed more than 60% of the shrub stems. As was the case with tree species, Burbank Island also had a high diversity of shrub/sapling species, including cottonwood, sandbar willow, roughleaf dogwood (*Cornus drummondii*), false wild indigo (*Amorpha fruticosa*), green ash, and peachleaf willow. In contrast to the other study sites, on Burbank Island, dogwood and wild indigo comprised most of the shrub stems (Figure 17). Other shrub/sapling species sampled across some of the reaches included riverbank grape (*Vitis riparia*), raspberry (*Rubus* sp.), white mulberry, and American and Siberian elms.

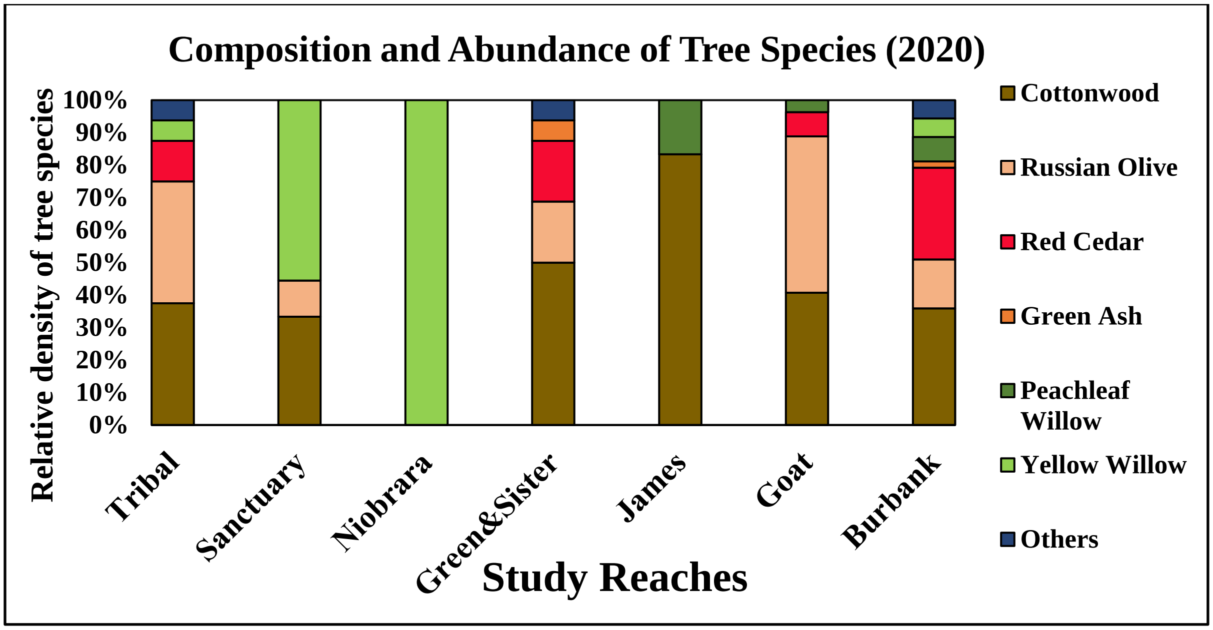


Figure 16: Dominant tree species across the seven study reaches. The ’Others‘ species category included white mulberry and American and Siberian elms.

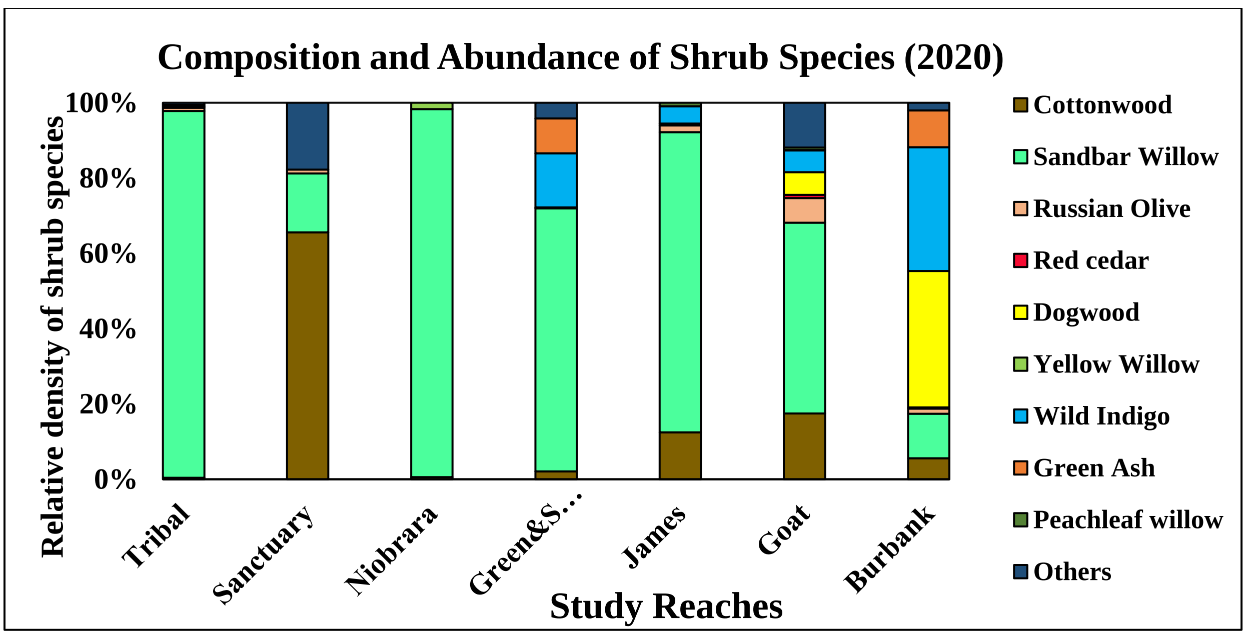


Figure 17: Dominant shrub species across seven study reaches. The ‘Others’ species category included grape, raspberry, white mulberry and American and Siberian elms.

3.4.2 Invasive species

In addition to documenting dominant tree and shrub species, I also analyzed the abundance of selected woody and herbaceous invasive plant species across the seven study reaches. Woody invasive plants were red cedar, Russian olive, Siberian elm, and salt cedar. Whereas redcedar was mostly dominant on the Burbank and Green & Sister Island sites, Russian olive was found at all seven reaches, with highest frequency of occurrence on Green & Sister Island. Siberian elm was encountered on only three reaches in the 59-mile segment: Burbank, Goat, and Green & Sister Island. Only Tribal Island had a plot containing a shrub-sized salt cedar (Figure 18).

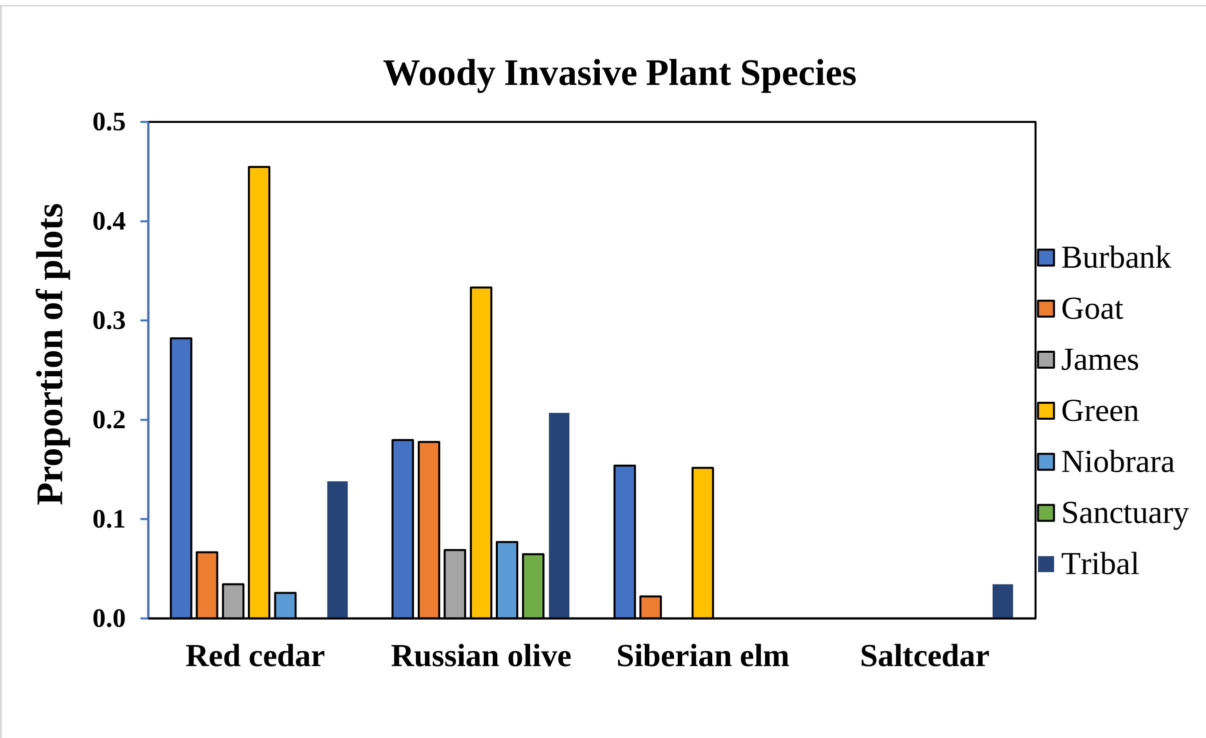


Figure 18: Occurrence of woody invasive species across the seven study reaches.

The invasive herbaceous plants species sampled in the seven sandbar reaches were Canada thistle, leafy spurge, common reed (*Phragmites australis*), purple loosestrife, reed canary grass, and sweet clover. Sweet clover was the most frequently encountered invasive species, present at moderate to high frequencies across all seven study sites (Figure 19). *Phragmites* was locally abundant on the Niobrara Confluence and Sanctuary Island sites. Nearly ninety percent of sample plots were found to have *Phragmites* at Niobrara and half of the plots in Sanctuary Island had this grass. The third most prominent invasive herbaceous plant species was purple loosestrife. It was found in all the study reaches except Green & Sister Island. Though in a smaller proportion of plots, Canada thistle was found in all the reaches. Burbank was the only reach where all six of these herbaceous invasive plant species were found.

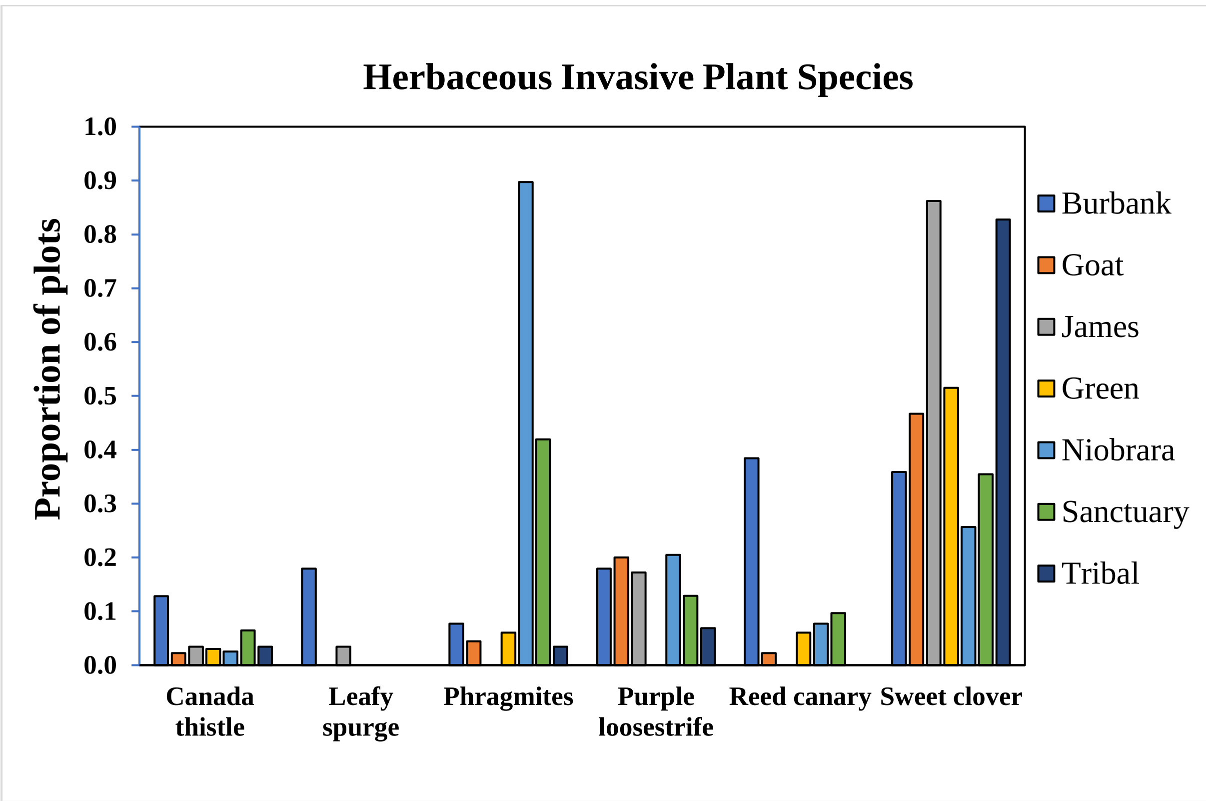


Figure 19: Occurrence of herbaceous invasive species across the seven study reaches.

4. Discussion and Conclusions

My first objective was to understand how vegetation and sandbar dynamics were impacted by the 2011 flooding in the MNRR area. My second objective was to explore the relationship between vegetation and sandbars, including how vegetation coverage affects sandbar formation and vice versa. My third objective was to investigate how geomorphology and topography affected the changes in landcover from 2012-2014/2016 in the MNRR. My fourth objective was to identify the dominant tree and shrub species and their patterns of abundance across the seven focal ‘set-aside’ sandbar reaches of the MNRR. My fifth and final objective was to examine the patterns of abundance of ten selected invasive plant species across the seven study reaches. I achieved the first and second objectives by analyzing the landcover time series maps of the seven study reaches from 2008-2016. The analysis of LiDAR imagery, statistical analysis of the relationship between relative elevation and original and new vegetation types, and the overlay of landcover change maps with erosion and deposition helped me achieve my third objective. Finally, the analysis of vegetation composition on unmanaged vegetated sandbars helped me achieve my fourth and fifth objectives.

I found that the 2011 flood strongly affected the vegetation and sandbar dynamics in the two segments of the Missouri National Recreational River. In 2008 all seven study reaches had more vegetated area compared to open sandbar area; however, the pattern reversed in 2012. All the study sites experienced a decrease in vegetation area and an increase in sandbar area from 2008 to 2012. The area of open sandbar habitat remained elevated, relative to pre-flood conditions, through 2014 and 2016, although vegetation increased, and sandbar area decreased on most study sites after 2012. These findings are similar to other studies that examined the effect of the 2011 flood on vegetation and sandbar dynamics along the Missouri River (i.e., Dixon et al. 2015; Sweeney et al. 2019; Beall et al. 2022). Sweeney et al. (2019) found vegetation to be a resisting force against erosion at small spatial extents in their study of eolian and fluvial geomorphic processes on three sandbars in the 59-mile segment of the MNRR. They compared pre-flood and post-flood images (years 2009, 2012, 2015) to explore how rates of fluvial and eolian erosion were related to sandbar locations relative to the thalweg of the Missouri River and wind direction. As with some of my sandbars, the area of their sandbars decreased over time, and they found fluvial erosion to be one of the main factors responsible for that (Sweeney et al. 2019). Like the vegetation, floodplain bird communities were also resilient to the effects of the flood. Munes et al. (2015) found that most bird species bounced back in two years after the flood, despite significant initial declines.

In my study, the effect of the 2011 flood varied across the seven study reaches. For example, among the three reaches in the 39-mile segment, the Niobrara Confluence experienced the highest proportional decrease in vegetation categories (i.e., forest and high canopy) and the highest increase in sandbar area from 2008-2016. The geographical location and topographic characteristics of the reach might have contributed to this outcome. Niobrara Confluence has a lower relative elevation range than the other two sites in the 39-mile segment and is also located at the confluence of the Niobrara River with the Missouri River. During the 2011 flood, sediment flow to this confluence was immense. Sediment supplies were likely heightened by large floods on the Niobrara River in the summer of 2010 (Beall et al. 2022). The combination of low site elevations and high sedimentation likely contributed positively to sandbar formation on this reach.

I found that the sandbar area generally declined in the years following the flood (2012-2016). Likewise, Sweeney et al. (2019) found that fluvial erosion has the potential to decrease the area of sandbars if it occurs along the margins of the sandbars. However, I found that vegetation expansion caused greater loss of sandbar area than did erosion, particularly on the 39-mile segment of the MNRR after 2012. In contrast to most other reaches, the sandbar area on the Niobrara Confluence reach did not decrease consistently with time after 2012. This may be because this reach receives large amounts of sediment from the Niobrara River. Although not occurring during the 2008-2016 time series, a record flood with a 500-year recurrence interval occurred in March 2019 on the lower Niobrara River, due to failure of the upstream Spencer Dam (Beall et al. 2022). It likely altered sandbar and vegetation areas further on the Niobrara Confluence reach and might have contributed to the low abundance and low species richness of trees (only four individual yellow willows) encountered during our sampling in 2020.

I observed that the mean Missouri River discharge was lower on the imagery dates in the pre-flood mapping year (2008) compared to the post-flood years (2012, 2014, 2016) for both the 39-mile and 59-mile segments (Tables A3 and A4). Across the imagery dates, the mean discharge was highest in 2012, right after the 2011 flood. Mean discharges were generally lower in 2014 and lowest in 2016. Among three reaches in the 39-mile segment, Niobrara had a higher mean discharge on the 2008 and 2016 imagery dates (Table A3). For 59-mile, Burbank had higher flow levels than the other reaches on the 2008, 2014, and 2016 image dates.

Based on the flow data, the mean discharge for most reaches (except for Burbank) in 2008 was lower, which should expose more sandbars, and the release was higher in 2012, which should expose less sandbar area. However, sandbars can grow during high flows by eroding sand from the riverbank or the riverbed and depositing it on bars. The higher the flood stage, the higher the bar can grow. During a flood, the bars tend to grow higher and wider while the deep channel erodes (Sweeney et al. 2019). Likewise, I found significant growth in sandbar area in 2012, as it might be associated with high water discharge.

Following 2012, the discharges on the imagery dates were within about 113 cms (4000 cfs) of each other, but decreased over time, meaning more sandbar could be exposed in the most recent year. Hence, the apparent growth in sandbar area that I found on the study reaches in the 39-mile segment (particularly Tribal Island) between 2014 and 2016 could have been an artifact of the slightly lower flow levels in 2016. However, sandbar areas on study sites in the 59-mile segment declined or remained relatively stable between 2014 and 2016. One possible reason is that the thalweg (deepest part of the channel) may have eroded more bar than was newly exposed by the decreasing discharge in the 59-mile segment (Sweeney et al. 2019). The more erosive environment on the 59-mile segment may also be reflected in the comparable areas of sandbar lost to erosion and vegetation there between 2012 and 2014, whereas sandbar losses were almost completely due to vegetation encroachment on the 39-mile segment. The channel in the 39-mile segment has not changed its position very much since 1894-1999, whereas numerous scars, wetlands, oxbow lakes, and abandoned chutes in the 59-mile segment signify a dynamic history of channel change (Elliott and Jacobson 2006). This might result in the bars being more stable, with their size mostly a function of discharge (i.e., shrinking when edges are flooded at high discharge, expanding when edges are exposed at low discharge) in the 39-mile segment. The existence of bars also indicates the channel complexity of these segments of the Missouri River (Elliott and Jacobson 2006).

The study reaches differed from one another in their mean relative plot elevations in both 2012 and 2014/2016, Burbank had a higher relative elevation compared to other study sites and study sites on the 59-mile segment consistently had higher relative elevations compared to study sites located in the 39-mile segment. One possible reason for the higher relative elevations might be greater amounts of channel incision on the 59-mile segment, where there are no downstream dams or delta effects. For example, since the completion of the dams, the cumulative decrease in tailwater stage below Gavins Point Dam was nearly 4 m and at Ft Randall it was 2.7 m according to a recent report by USACE (USACE, 2017). Furthermore, the effects of the Niobrara/Lewis and Clark delta could have contributed to increases in channel bed elevation (or at least not as much incision) on the two downstream sites on the 39-mile segment. Analysis of historical cross section surveys shows that channel incision has been the dominant process in the Tribal Island reach, which is 5 km downstream from Fort Randall Dam, whereas significant aggradation of the channel bed has occurred at the Niobrara confluence. The reach containing Sanctuary Island, approximately 25 km downstream from Fort Randall Dam and 12 km upstream from the Niobrara confluence, has shown relatively little cumulative change or slight bed aggradation. In contrast, essentially the entire 59-mile segment shows net incision (Elliott and Jacobson, 2022).

With the help of ArcGIS, I performed change analysis of the landcover types from 2012 to 2014/2016. I visualized the changes by using landcover change maps and documented the conversion area, with my focus being to highlight the patterns of new vegetation and lost vegetation across the study reaches. I found generally similar characteristics on the 39-mile and 59-mile segments, although some differences existed between study reaches located in those segments. For example, most sites on both the 39-mile and 59-mile segments experienced more new vegetation from 2012-2014/2016 compared to lost vegetation. This pattern indicated that gradually after the 2011 flood event, vegetation colonization occurred on these two segments. Similarly, Beall et al. (2022) found in their research that woody vegetation increased on the Lewis and Clark Lake delta-backwater during 2012-2016, after initially declining after the 2011 flood. However, the growth of new vegetation was not equal across the seven reaches in our study. The Niobrara Confluence reach showed a decrease in vegetation coverage as it experienced more lost than new vegetation from 2012-2016.

I explored the relationships between post-flood geomorphic change and landcover change in two ways: 1) visualization of overlays between elevation change maps and landcover change maps and 2) analysis of variance of elevation changes (erosion vs. deposition) between landcover change types. I found that for all seven study reaches, the most dominant landcover change category from 2012-2014/2016 was remain vegetation (vegetation-vegetation). The inspection of elevation change maps revealed that, of the seven study reaches, only Tribal, Niobrara Confluence, and Burbank Island showed notable areas of significant erosion and deposition from 2012-2014/2016. As determined previously, the threshold value for statistically significant geomorphic change was ±0.22 m, and the elevation change maps on most of the reaches showed no significant elevation changes from 2012-2014/2016. In contrast, almost half of the terrestrial area on the Niobrara Confluence reach showed deposition ranging from 0.22 to 1.54 meters, and about one-third of the area of Tribal Island experienced erosion ranging from -1.10 to -0.22 m. Burbank had some strong erosion along banks, ranging to more than 2.42 m of elevation loss.

The observation that the highest elevation change was observed for islands of the Missouri-Niobrara confluence reach may be explained by the contribution of the Niobrara River. The Niobrara confluence reach receives suspended and bedload sediments from the Niobrara River, with many braided bars which are subject to mostly aggradation. The lower portion of the Niobrara River has been experiencing a base-level rise since the mid-1950s. Skelly et al. (2003) found this aggradation to be up to 3 m in the lower 14 km of the Niobrara River. Sediment compositional data show that fifty percent of the sand in the Lewis and Clark delta originated from the Niobrara River (Sweeney et al. 2016). Besides this, there are other tributaries in the 39-mile segment such as Choteau Creek, Emanuel Creek, Ponca Creek, and Bazile Creek, which contribute sediment to the Niobrara confluence and the delta after it. In the delta, approximately 45% of the sediment comes from the Niobrara River and another 45% from the Missouri River, with the remaining 10% derived from these other tributaries and from bank erosion of Lewis and Clark Lake (Sweeney et al., 2016). However, according to more recent study, the Niobrara contributes 54%, the Missouri 36%, and the other tributaries make up the remaining 10%. Whereas the Niobrara River is an important sediment source during normal flows, the Missouri River is an important source of sediment during high flows (Sweeney and Cowman 2018)

Tributaries in the 59-mile segment may also influence the downstream study reaches. For example, Jurotich et al. (2021) found Bow, Lime, Turkey and Aowa creeks in Nebraska and the James, Vermillion, and Big Sioux rivers in South Dakota to be sources of sediment and nutrients for the islands on the 59-mile segment, even though sediment transport in the Missouri River below Gavins Point Dam has been reduced to 0.2% of its original, pre-dam load (Jacobson et al. 2009). They showed that South Dakota tributaries currently contribute ~80 % and the Nebraska tributaries accounts for less than 5% of the suspended sediment load to the 59-mile MNRR segment (Jurotich et al. 2021).

Visual inspection of elevation and landcover change maps, as well as ANOVA and posthoc analyses of point-level changes, indicated a significant association between vegetation change type and elevation change. Elevation changes and landcover change maps (i.e., Figures 14 and 15) revealed that in areas with no significant elevation changes, the dominant category was ‘remain vegetation’. In areas with higher erosion (e.g., Burbank), the dominant vegetation change category was ‘sandbar-water’. In areas with higher deposition (e.g., Niobrara), the dominant change categories were ‘sandbar-vegetation’ and ‘water-sandbar.’ Mean relative elevations also differed among different original vegetation types and among the different study reaches. The relative elevation of forest was higher (although not always significantly) than other vegetation categories in the 39-mile and 59- mile segments.

Statistical analysis also revealed that elevation change (erosion vs. deposition) from 2012-2014/2016 differed among vegetation change types. Points in the ‘remain vegetation’ category averaged 0.12 m of deposition from 2012-2014/2016 across the study reaches. However, the deposition is significantly lower for points located in two of the other three categories (remain sandbar, lost vegetation) as they have negative mean values, which suggests net erosion. These patterns may reflect the effects of vegetation on fluvial and eolian geomorphic processes, with established vegetation helping to stabilize surfaces and induce deposition (Sweeney et al. 2019). Corenblit et al. (2011) discusses such an interconnection among pioneer herbaceous species and modifications of topography, and sediment dynamics in single channels and island braided channels. Similarly, Gurnell et al. (2012) found that some riparian woody plants function as ecosystem engineers in building islands and bars and emphasized the importance of vegetation-physical process interactions for fluvial morphodynamics.

Among the seven study reaches James River Island had the highest relative abundance of cottonwood trees. On all other reaches except Niobrara Confluence at least 30% of the trees were cottonwoods. This means that, despite concerns about cottonwood decline along the Missouri River (Dixon et al. 2012; Johnson et al. 2012), successful cottonwood recruitment and persistence occurred during the development of these early successional sites within the MNRR. However, Russian olive and redcedar, which are invasive tree species, are also abundant on all reaches except Niobrara Confluence and James River Island. Sandbar willow was found to be the most abundant shrub species on five of the reaches. Sandbar willow is an early successional riparian species found to be concurrently existing with cottonwoods in other studies (Dixon et al. 2010). Also, sandbar willow can stabilize sandbars by creating slack-water zones which trap, as well as protect, sands (Rood et al. 2001). Therefore, it is possible that these abundant willows will facilitate cottonwood regeneration on these reaches of the MNRR. Sweet clover was the most abundant herbaceous invasive species in all reaches. Elsewhere, it has been found to negatively affect the growth of woody seedlings and herbaceous species or outcompete them for soil moisture and soil nutrients (Stromberg 1997).

This study will enable us to learn about the response of riparian vegetation (i.e., cottonwood, pioneer herbaceous species, sandbar willow, and Russian olive) to geomorphologic disturbances on these segments of the Missouri River, as well as the influence that the vegetation has on geomorphic processes. The analysis of the temporal dynamics of sandbars may help management agencies (NPS and USACE) understand how the sandbars in the study areas have evolved due to historical (i.e., 1997, 2011) flood events, as well as how riparian ecosystems have developed and expanded following the floods. A further useful step will be to extend these analyses using 2020 landcover maps and LiDAR data that are just now being made available from the USACE. Knowing about the composition, distribution, and density of vegetation on the sandbars, and how these are related to water levels, may also help NPS and USACE determine how to best manage and maintain flows in the Missouri River. This could include working with river hydrologists and engineers to modify flows in ways that can minimize the adverse impacts of Missouri River flow releases on the riparian ecosystem and species living in it. This river/sandbar management is crucial to support emergent habitats for threatened species (i.e., Piping Plover) on the sandbars, as well as riparian vegetation that supports multiple species of land birds and other wildlife (Swanson 1999; Gentry et al. 2006; Munes et al. 2015). Besides preserving habitats for threatened bird species, the National Park Service also seeks to protect other Outstandingly Remarkable Values (ORVs) related to the MNRR's scenic, recreational, geological, fish and wildlife, historical, cultural, and botanical features. Overall, the knowledge of the status, trajectories of change, and biological values of these sandbars is essential for informing management by NPS to preserve, protect, and enhance riparian ORVs.

The results and findings of this study about the geomorphology and vegetation structure across these two segments of the Missouri River may be crucial for sedimentologists, riparian ecologists, and especially the National Park Service (NPS). NPS can play a vital role in ensuring a bare, moist surface which is a suitable environment for cottonwood regeneration in the MNRR. The USACE should also engage members of the local community as a stakeholder group. They might get insights from different expert groups of the community on how to better manage water levels during a flood so that all stakeholder groups benefit from this management. For example, in Manitoba, Canada the 1997 Red River Flood was tackled by three rural communities through successful community preparedness and response. The historical relationship between the government and the communities also helped them to mitigate the consequences of the disaster, because the communities and the provincial and federal governments have been partners to enhance preparation and response to periodic Red River flooding since the 1966 flood (Buckland and Rahman 1999). Similarly, Best and others (2007) discuss a need for a 'holistic management approach' to benefit from, cope with, and plan for floods in the Brahmaputra-Jamuna River, a dynamic alluvial river in Bangladesh.

This study has five major limitations. First, the area mapped for the study sites was slightly different between different years. In general, the total area was lower for the year 2008 across the seven study reaches. This happened because of inconsistent mapping categories by USGS for landcover types. For example, they did not have a forest category for the 2016 maps. So, I had to digitize forest area from the previous year's map. In addition, I excluded upland habitat types (i.e., Terrace and Valley Wall), which could affect the total mapping area if they were not consistently identified as upland in the different years. Second, due to cloud coverage and data unavailability (i.e., LiDAR was unavailable for 2014 for the 39-mile segment and for 2016 for the 59-mile segment), I compared the vegetation transition and elevation change for different date intervals for the 39-mile (2012-2016) and 59-mile (2012-2014) segments. This could have affected the analysis, as the longer time-period would have had a different flow history that might have had different impacts on deposition and erosion. Third, I randomly selected my sampling points within early successional habitats, and their locations may vary within the vegetation categories. For example, some parts of the established forest on Burbank Island were sampled as early successional vegetation, whereas the established forest on the other islands was not sampled, with the exception of Sister & Green Island. However, the forest on Burbank is younger than that on the main islands of Goat, James River, and Sanctuary Island. Sampling the more established vegetation on Burbank and Sister & Green islands could have affected species composition of the vegetation (e.g., the higher diversity of woody species on Burbank Island), as well as the elevation distribution of the sampling points.

Fourth, the images I used for analysis were derived from different satellite missions and had varied resolutions. For example, the maps for 2008 used Quick Bird imagery, which had a pixel resolution of 0.6 m, whereas for 2014 and 2016, the maps used Rapid Eye, which had a coarser pixel resolution of 6 m. The vertical and horizontal resolution of the DEMs derived from LiDAR also differed across the study years. Fifth and final, the flow discharge was inconsistent between maps since they were based on images from different dates. This could result in inconsistent estimates of sandbar area, as lower flows will expose greater areas of existing bars, while higher flows will cover more of the sandbar surface. High flow can initiate the process of both aggradation and erosion and can affect the formation of sandbars. In addition, bars growth or erosion ultimately have to do with the sediment supply: if there is a low sediment supply, the bars will not grow; if there is a high sediment supply, the bars can grow very large. The sediment supply downstream of dams decreases over time due to the lowering of base level and erosion of the channel below the dam. Future studies should incorporate most recent LiDAR and sandbar maps available (year 2020) in order evaluate post-2016 changes in geomorphology and vegetation within set-aside sandbars in the MNRR.

References

Beall, C.C., Dixon, M.D., Illeperuma, N.D., Sweeney, M.R. and Johnson, W.C., 2022. Expansion of woody vegetation on a Missouri River reservoir delta-backwater. *Ecohydrology*, 15(1), e2357. https://doi.org/ 10.1002/eco.2357.

Best, J. L., Ashworth, P. J., Sarker, M. H., and Roden, J. E. 2007. The Brahmaputra-Jamuna River, Bangladesh. In A. Gupta(Ed). *Large Rivers: Geomorphology and Management* (pp. 395 433). Wiley.

Buckland, J., and Rahman, M. 1999. Community-based disaster management during the 1997 Red River Flood in Canada. *Disasters*, 23(2), 174-191.

Corenblit, D., Baas, A. C., Bornette, G., Darrozes, J., Delmotte, S., Francis, R. A., Gurnell, A. M., Juieln, F., and Steiger, J. 2011. Feedbacks between geomorphology and biota controlling Earth surface processes and landforms: A review of foundation concepts and current understandings. *Earth-Science Reviews*, 106(3-4), 307–331. doi: 10.1016/j.earscirev.2011.03.002

Dixon, M. D., C. J. Boever, V. L. Danzeisen, C. L. Merkord, E. C. Munes, M. L. Scott, W. C. Johnson, and T. C. Cowman. 2015. Effects of a "natural" flood event on the riparian ecosystem of a regulated large-river system: the 2011 flood on the Missouri River, USA. *Ecohydrology* 8(5):812-824. (DOI: 10.1002/eco.1613).

Dixon, M.D., Johnson, W.C., Scott, M.L. and Bowen, D., 2010. Status and trend of cottonwood forests along the Missouri River. Geological Survey Fort Collins Co Biological Resources Div.

Dixon, M.D., W.C Johnson, M.L. Scott, D. Bowen, and L.A Rabbe. 2012. Dynamics of plains cottonwood (*Populus deltoides*) forests and historical landscape change along unchannelized segments of the Missouri River, USA. *Environmental Management* 49:990–1008

Elliott, C. M., and Jacobson, R. B. 2006. Geomorphic classification and assessment of channel dynamics in the Missouri National Recreational River, South Dakota and Nebraska . *US Geological Survey* 2006-5313.

Elliott, C..M, and Jacobson, R.B. 2022. Data release for Scientific Investigations Report: Sixty years of channel adjustments to dams in the two segments of the Missouri National Recreational River, South Dakota and Nebraska, U.S. Geological Survey Digital Data Release https://doi:10.5066/P9RZPNJR.

Finch, D.M. and L.F. Ruggiero. 1993. Wildlife habitats and biological diversity in the Rocky Mountains and northern Great Plains. *Natural Areas Journal* 13:191–203.

Galat, D. L., and Lipkin, R. 2000. Restoring ecological integrity of great rivers: historical hydrographs aid in defining reference conditions for the Missouri River. *Assessing the Ecological Integrity of Running Waters*, 29–48. doi: 10.1007/978-94-011-4164-2_3.

Grigg, N., McCarthy, C., Lawrence, B., and Ockerman, D. 2011. Review of the regulation of the Missouri River mainstem reservoir system during the flood of 2011. Consultant report to the U.S. Army Corps of Engineers.

Gurnell, A. M., Bertoldi, W., and Corenblit, D. 2012. Changing river channels: The roles of hydrological processes, plants and pioneer fluvial landforms in humid temperate, mixed load, gravel bed rivers. *Earth-Science Reviews*, 111(1-2), 129–141. doi: 10.1016/j.earscirev.2011.11.005.

Jacobson, R. B., Blevins, D. W., and Bitner, C. J. 2009. Sediment regime constraints on river restoration—An example from the lower Missouri River. *Geological Society of America Special Paper*, 451, 1–22. https:// doi.org/10.1130/2009.2451(01)

Johnson, W. C., R. L. Burgess, and W. R. Keammerer. 1976. Forest overstory vegetation and environment on the Missouri River floodplain in North Dakota. *Ecological Monographs* 46(1): 59-84.

Johnson, W.C., M.D. Dixon, M.L. Scott, L. Rabbe, G. Larson, M. Volke, and B. Werner. 2012. Forty years of vegetation change on the Missouri River floodplain. *BioScience* 62(2):123–135.

Jurotich, M., Cardona, N., Vázquez, B., Wetzel, R., Cowman, T., and Sweeney, M. 2021. Contributions of suspended load from Missouri River tributaries, southeast South Dakota, and northeast Nebraska: Building a sediment budget. *River Research and Applications*, 37(4), 511-521. doi.org/10.1002/rra.3767

Maxwell, Ted A. 1982. [Report] Sand Sheet and Lag Deposits in the Southwestern Desert. NASA. https://repository.si.edu/handle/10088/6385.

Mietz, Steve. n.d. Outstandingly Remarkable Values. National Park Service. U.S. Department of Interior. 1982

Munes, E. C., Dixon, M. D., Swanson, D. L., Merkord, C. L., and Benson, A. R. 2015. Large, infrequent disturbance on a regulated river: response of floodplain forest birds to the 2011 Missouri River flood. *Ecosphere*, 6(11). doi: 10.1890/es15-00007.1

Nefas, S. M., Hunt, K. L., Fraser, J. D., Karpanty, S. M., and Catlin, D. H. 2018. Least Tern (*Sternula antillarum*) nest success and chick survival on the Missouri River following historic flooding. *The Wilson Journal of Ornithology* 130(2):371–376.

Pegg, M. A., Pierce, C. L., and Roy, A. 2003. Hydrological alteration along the Missouri River Basin: A time series approach. *Aquatic Sciences* - Research Across Boundaries, 65(1), 63–72. doi: 10.1007/s000270300005

Rood, S. B., Goater, L. A., Gill, K. M., and Braatne, J. H. 2011. Sand and sandbar willow: a feedback loop amplifies environmental sensitivity at the riparian interface. *Oecologia*, 165(1), 31-40. doi: 10.1007/s00442-010-1758-2

Selkirk, P., Adamson, D., and Seppelt, R. 1988. Terrace types and vegetation dynamics on Macquarie Island. *Papers and Proceedings of The Royal Society of Tasmania*, 122(1), 59–64. doi: 10.26749/rstpp.122.1.59

Skelly, R. L., Bristow, C. S., and Ethridge, F. G. 2003. Architecture of channel-belt deposits in an aggrading shallow sandbed braided river: the lower Niobrara River, northeast Nebraska. *Sedimentary Geology*, 158(3-4), 249-270. doi:

Stromberg, J. C., & Chew, M. K. 1997. Herbaceous exotics in Arizona's riparian ecosystems. *Desert Plants*,13(1) (June 1997), 11-17.

Strong, L.L. 2012. Extending A Prototype Knowledge- And Object-Based Image Analysis Model To Coarser Spatial Resolution Imagery: An Example From The Missouri River. 4th GEOBIA, May 7-9, 2012 - Rio de Janeiro - Brazil. p.530

Swanson, D. L. 1999. Avifauna of an early successional habitat along the middle Missouri River. *Prairie Naturalist* 31(3):145–164

Swanson, D. L., Dean, K. L., Carlisle, H. A. and Liknes, E. T. 2005. Riparian and woodlot landscape patterns and migration of Neotropical migrants in riparian forests of eastern South Dakota. – In: Ralph, C. J. and Rich, T. D. (eds), *Bird conservation implementation and integration in the Americas: proceedings of the third international Partners in Flight conference 2002*. Gen. Tech. Rep. PSW-GTR-191. Albany, CA, Pacific Southwest Research Station, Forest Service, U.S. Dept of Agriculture, pp. 541 – 549.

Sweeney, M. R., Fischer, B., Wermers, K., and Cowman, T. 2019. Eolian and fluvial modification of Missouri River sandbars deposited by the 2011 flood, USA. *Geomorphology*, 327, 111–125. doi: 10.1016/j.geomorph.2018.10.018.

Sweeney, M.R., Cowman, T., Dixon, M., and Wesner, J. 2016. Characterization of the geomorphology, sediment sources, vegetation, and macroinvertebrate diversity of the Lewis and Clark Lake delta. The University of South Dakota Missouri River Institute and the Missouri Sedimentation Action Coalition. 53 p.

Sweeney, M.R., Cowman, T., 2018, Sediment sources of the Lewis and Clark Lake delta, Missouri River. Geological Society of America Abstracts with Programs, v. 50, no. 4.

US Army Corps of Engineers (USACE). 2017. Missouri River Stage Trends. Technical Report. Missouri River Basin Water Management Division, Omaha, Nebraska.

US Geological Survey (USGS). 2005. Cottonwood in the Missouri Breaks National Monument. U.S. Department of the Interior, U.S. Geological Survey. Fact Sheet 2005-3132

Wheaton, J. M., Brasington, J., Darby, S. E., and Sear, D. A. 2010. Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. *Earth surface processes and landforms: the journal of the British Geomorphological Research Group*, 35(2), 136-156.

APPENDICES

Appendix A

Table A1: Year of the land cover maps used in this analysis.

Study Sites	Year used in this study			
Tribal	2008	2012	2014	2016
Sanctuary	2008	2012	2014	2016
Niobrara	2008	2012	2014	2016
Green & Sister	2009	2012	2014	2016
James	2009	2012	2014	2016
Goat	2008	2012	2015	2016
Burbank	2009	2012	2014	2015

Table A2: Comparison of relative sandbar and vegetation area between year 2008-2016.

	Study Sites	2008		2012		2014		2016	
		Veg	Sandbar	Veg	Sandbar	Veg	Sandbar	Veg	Sandbar
39-mile	Tribal Island	96%	4%	67%	33%	87%	13%	64%	36%
	Sanctuary Island	98%	2%	56%	44%	85%	15%	84%	16%
	Niobrara Island	99%	1%	47%	53%	60%	40%	44%	56%
59-mile	Green& Sister Island	97%	3%	53%	47%	68%	32%	70%	30%
	James River Island	97%	3%	69%	31%	77%	23%	85%	15%
	Goat Island	83%	17%	51%	49%	74%	26%	68%	32%
	Burbank Island	100%	0%	30%	70%	52%	48%	47%	53%

Table A3: Comparison of sources, resolutions and mean discharge among the reaches of 39-mile segment.

Year	Reaches	Dates	Satellites	Resolution (m)	Discharge (cfs)	Discharge (cms)
2008	Tribal	20 July 2008	QuickBird	0.6 * 0.6	17,700	501.2
	Sanctuary					
	Niobrara	07 August 2008			20,900	591.8
2012	Tribal	02 June 2012	GeoEye	0.4* 0.4	28,700	812.7
	Sanctuary					
	Niobrara					
2014	Tribal	28 May 2014	RapidEye	6*6	26,700	756.1
	Sanctuary					
	Niobrara					
2016	Tribal	23 July 2016	RapidEye	6*6	24,100	682.4
	Sanctuary	25 July 2016			24,700	699.4
	Niobrara					

Table A4: Comparison of sources, resolutions and mean discharge among the reaches of 59-mile segment.

Year	Reaches	Dates	Satellites	Resolution (m)	Discharge (cfs)	Discharge (cms)
2008	Green & Sister	05 August 2009	QuickBird	0.6 * 0.6	27,500	778.7
	James	23 August 2009			26,000	736.2
	Goat	15 July 2008			14,000	396.4
	Burbank	28 September 2009			31,500	892.0
2012	Green & Sister	4 June 2012	GeoEye	0.4 * 0.4	31000	877.8
	James					
	Goat					
	Burbank		RapidEye	6 * 6		
2014	Green & Sister	27 May 2014	RapidEye	6*6	30,000	849.5
	James					
	Goat	18 July 2015			27,000	764.6
	Burbank	6 June 2014			30,000	849.5
2016	Green & Sister	26 July 2016	RapidEye	6*6	25,000	707.9
	James					
	Goat					
	Burbank	17 July, 2015			26,900	761.7

Table A5: Horizontal and vertical accuracy of LiDAR data (https://coast.noaa.gov/inventory/).

LiDAR year	Vertical accuracy (cm)	Horizontal accuracy (cm)	Source
2012	18.5	100	Nebraska NRCS LiDAR Project
2014	12.5	60	U.S. Army Corps of Engineers (2014 Missouri River low water LiDAR collection project)
2016	7.19	Not Provided	USGS (2016 South Dakota Lidar - SPL)
2016	6.9	60	USGS (2016 Hat Creek/White River NE Lidar)

Table A6: Mean Water level for 39-mile segment for year 2012 and 2016 (elevation in meter)

	2012 (m)	2016 (m)
Tribal	375.57	375.31
Sanctuary	373.21	372.50
Niobrara	371.73	372.26

Table A7: Mean Water Level 59-mile segment for year 2012 and 2014 (elevation in meter)

	2012 (m)	2014 (m)
Green & Sister	351.94	350.57
James	349.96	348.94
Goat	345.62	344.68
Burbank	338.59	338.12

Appendix B

Date:__________ Site Code:________________ Plot ID:_________ Plot Type (Circle): Nest / Random / Bird Point

GPS Coordinates:___________________, ___________________Observers:__________________________

Data Sheet for Vegetation Sampling – revised 7/9/19

Cover Codes: **0** = 0% (**no cover**), **1** = 1-33% (**sparse**), **2** = 33-67% (**medium**), **3** = 67-100% (**high**)

	Vegetation Volume (0-5 m) or Canopy Cover (> 5 m) Classes (within 3 m radius for 0-5 m strata, within 10 m radius for > 5 m strata)																			
	Quadrant 1 (NE)					Quadrant 2 (SE)					Quadrant 3 (SW)					Quadrant 4 (NW)				
Species	0-0.5 m	0.5-2 m	2-5 m	5-10 m	>10 m	0-0.5 m	0.5-2 m	2-5 m	5-10 m	>10 m	0-0.5 m	0.5-2 m	2-5 m	5-10 m	>10 m	0-0.5 m	0.5-2 m	2-5 m	5-10 m	>10 m
Tot Veg Cov																				

Dominant Species by Layer (all quads)					
Cottonwood					
Russian olive					
Red Cedar					
Dogwood					

Notes:

	Woody Stem Densities and beaver-chewed stems (BV)												
	Shrub/Sapling Stems (<10 cm dbh, >0.5 m tall) in 3 m radius					# Tree Stems (≥10 cm dbh) in 10 m radius plot							
Species	<2.5 cm	BV	2.5-10 cm	BV	Total	10-20 cm	BV	20-40 cm	BV	40-80 cm	BV	>80 cm	BV

		Invasive Species Coverage (Canopy or Ground Cover) **Cover Codes**: **0** = 0% (**no cover**), **1** = 1-33% (**sparse**), **2** = 33-67% (**medium**), **3** = 67-100% (**high**); All growth forms combined (seedling, sapling, tree, etc.)	
Species	**Cover code**	**Comments**	**Growth Form(s)**
Other			

Invasive tree species: Ph=*Phragmites* (reed), PL=Purple loosestrife, SC=Saltcedar (*Tamarix*), RO=Russian-olive, RC=Redcedar, SE=Siberian Elm

Distance to non-woodland edge (m from plot center):______ Describe:

Figure B1: Datasheet used for vegetation sampling during summer field work, 2019 and 2020.

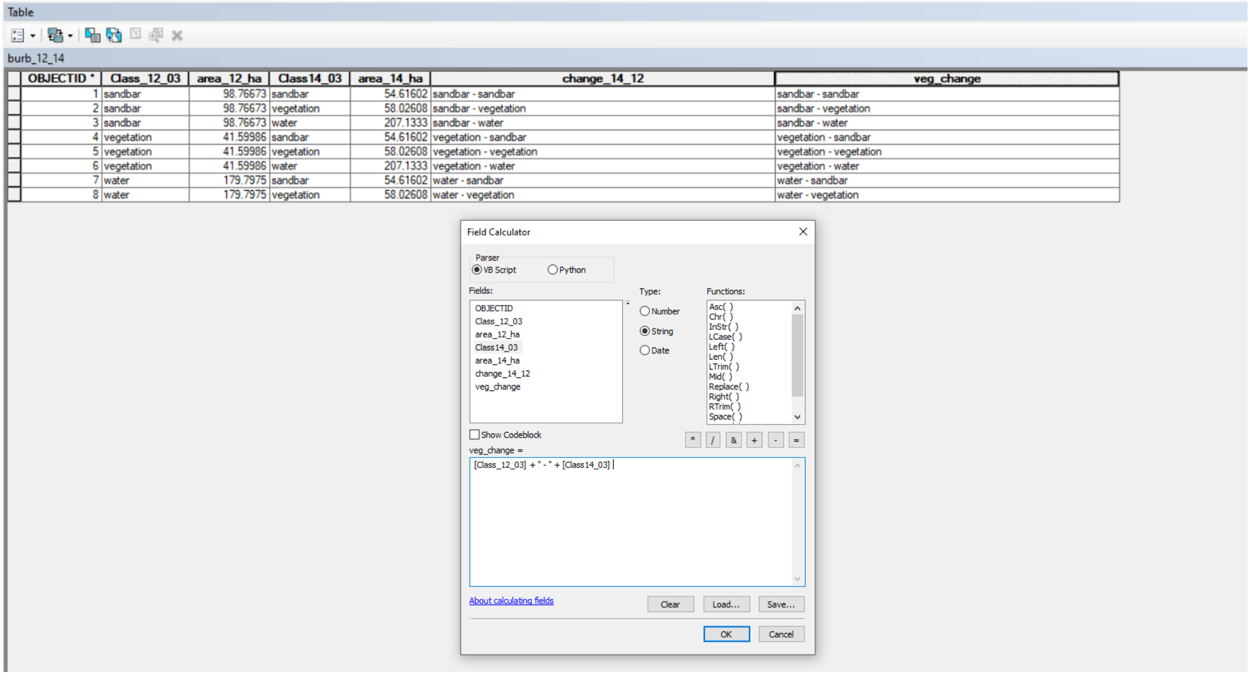


Figure B2: Example of use of field calculator in ArcGIS for vegetation change categories.

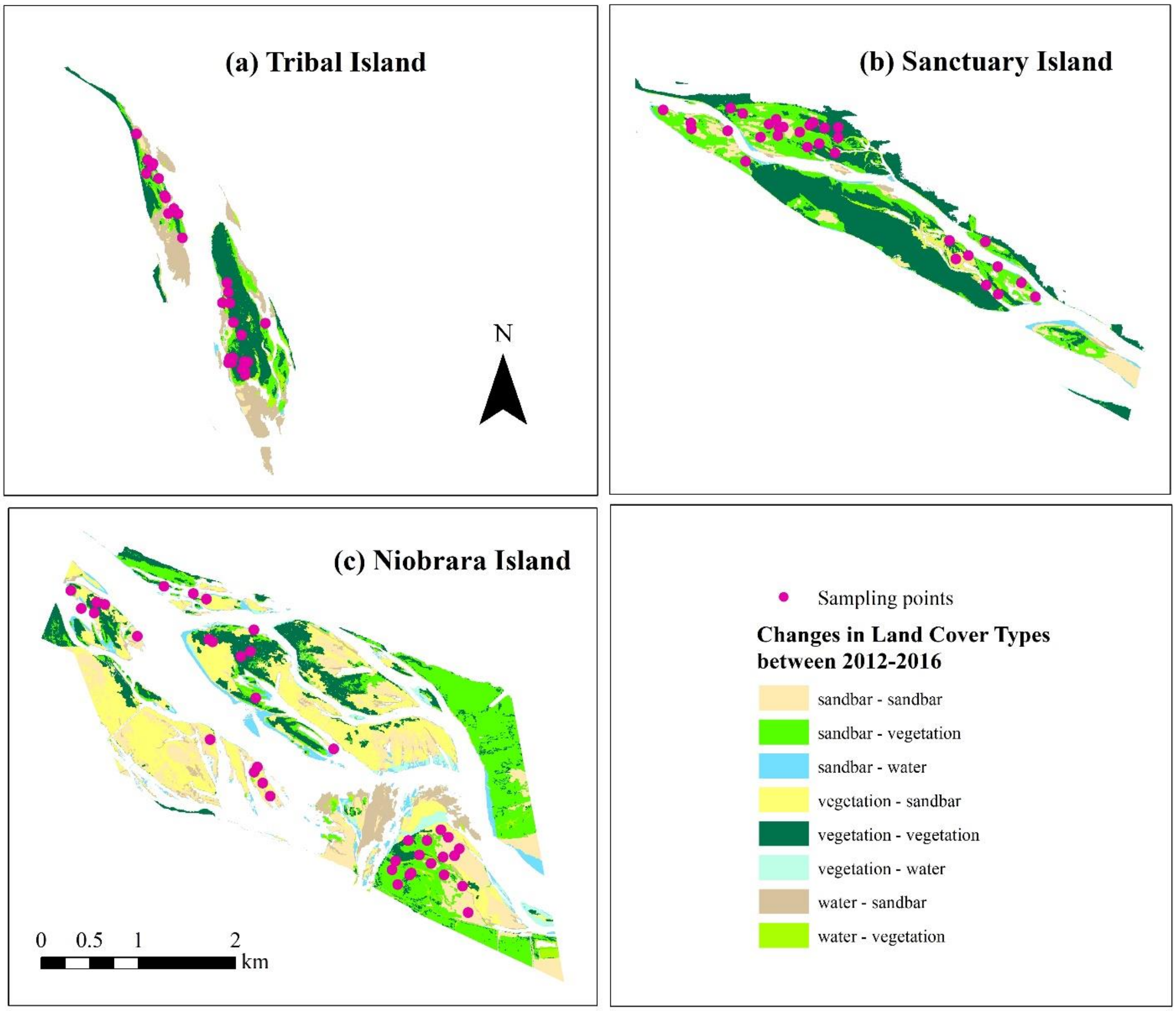


Figure B3: Overlay of sampling points across three sites (a) Tribal, (b) Sanctuary, and (c) Niobrara Island in the 39-mile segment of the MNRR.

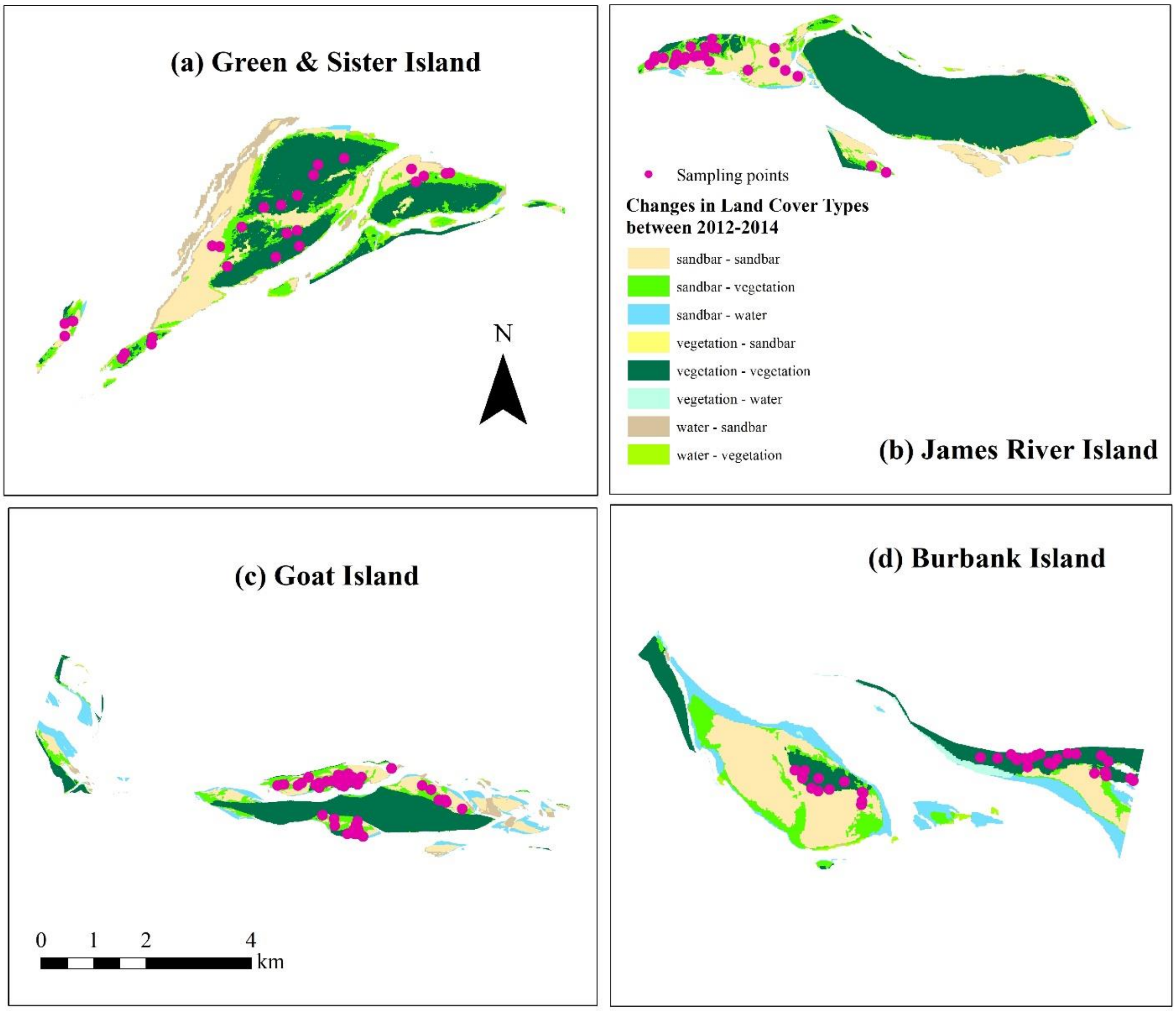


Figure B4: Overlay of sampling points across four sites (a) Green & Sister, (b) James River, (c) Goat, and (d) Burbank Island in the 59-mile segment of the MNRR.