Christopher Farm & Gardens Bluff Retreat Report

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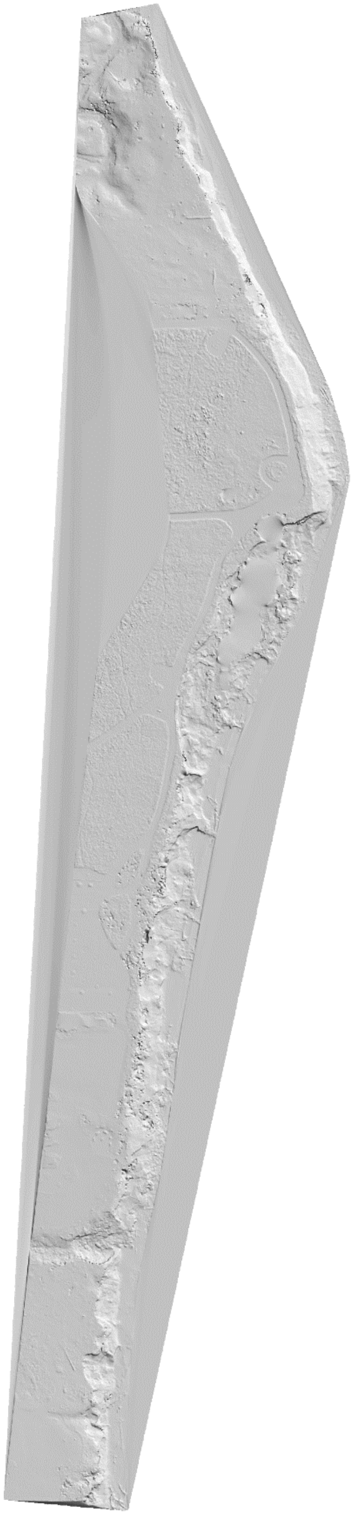


Introduction

Coastal bluff recession is a natural process driven by wave erosion at the bottom of the bluff and downcutting of the foreshore and shoreface, followed by an upslope progression of bluff failure. Methods of large-scale (10's of to 100's of feet) failure include blockfalls, slumps, slides, and flows. Precipitation, wind, and groundwater seepage can also play an important role in bluff erosion, and this effect is typically largest on slopes lacking vegetative cover. Groundwater seepage can rapidly undercut overlying slopes, especially when seeps flow from porous sand and gravel materials.

Over long timescales (multiple decades to centuries), bluff retreat can be approximated by equal recession of the bluff toe and crest at a quasi-constant slope angle. Over shorter time scales dynamic perturbations (water level rises, precipitation and wind events, ice cover variability) can lead to non-parallel retreat, where the slope angle fluctuates. While the parallel retreat concept does not include many potentially important small-scale processes, it is useful for understanding bluff recession over long time scales. In reality, bluff recession is highly episodic, with periods of relatively little erosion punctuated by rapid erosion events (storms, intense precipitation and freeze-thaw events).

The stable slope angle setback approach is based on the hypothesis that over long time scales and at equilibrium conditions, a slope is expected to reach a stable angle that is governed by the geotechnical properties of the slope. At a particular angle, the slope will achieve physical equilibrium between the forces that are driving the slope to fail, namely gravity, and the forces that are resisting failure, namely friction and cohesion between the grains that make up the slope. Absent erosion at the toe of the slope or changes to the groundwater or loading conditions, the slope would be expected to remain at this stable angle and erode only by surficial processes (sheetwash, root throw, solifluction, etc.), rather than by mass movements such as slumps and slides.

To better understand potential erosion along this reach, we measured retreat rates and steepening of the bluff from aerial orthophotos, LiDAR elevation data, and structure-from-motion (SfM) derived data acquired via low-altitude uncrewed aerial system (UAS) flights. We then applied a stable slope angle setback analysis to generate potential setback distances for infrastructure with an expected lifespan of 5, 10, or 20 years.

Methods

Table 1. List of data used for these analyses, including data type, date of acquisition, and resolution.

Type	Date	Resolution	Link
DEM (LiDAR)	??/??/2004	1.5 m downsampled to 0.6 m	https://www.sco.wisc.edu/data/elevationlidar/
Orthophoto (Aerial)	Spring 2014	0.3 m	https://www.arcgis.com/apps/webappviewer/index.html?id=35e7695029f9494981dc1a18a47a9e5f
Orthophoto (SfM)	12/21/2020	0.02 m	See data package
DEM (SfM)	12/21/2020	0.10 m	See data package

Data Projection and Translation: Data from several sources were employed in this analysis (Table 1). The 2020 data (EPSG: 32616) were first projected into the coordinate systems of the 2004 (EPSG: 3071) and 2014 (EPSG: 8158) data. The 2014 and 2004 data did not appear to be in alignment with the 2020 data or each other based upon visual inspection. The 2020 data were separately horizontally translated to achieve 2D alignment with both the 2004 and 2014 data prior to computation. The 2020 data were shifted 4.78 ft

East and 23.01 ft South to achieve horizontal alignment with the 2014 orthophoto. The 2020 data were shifted 15.26 ft West and 13.88 ft South to achieve horizontal alignment with the 2004 elevation data.

Recession and slope angle analysis: Recession rates were calculated between Spring 2014 (assuming the photos were acquired on 05/01/2014) and 12/21/2020. The bluff toe and crest were manually digitized from the 2014 orthophoto and 2020 datasets. The digitized shoreline features were then projected into a UTM projection (EPSG:32616) for recession analysis. Transect analysis was performed using the Digital Shoreline Analysis System (DSAS, Thieler et al., 2009) with a one meter transect spacing. To facilitate slope angle measurements, the intersections of the transects and the shoreline features were then projected and shifted to align with elevation data in the statewide projection system (EPSG: 3071), and the elevations from 2004 and 2020 at these points were extracted. This analysis assumes that no significant toe erosion took place in the low water years from 2004-2014. This assumption appears reasonable based on visual inspection of the data. We computed a single angle for each transect based on these two points. Angle calculations were spot checked on elevation profiles. Uncertainties in crest and toe positions propagate to these calculations but were not quantified. To examine profile changes along the bluff, the transects used for recession analysis were reprojected to EPSG: 3071 and elevation values along the transects were extracted from the 2004 and 2020 elevation data at a 1 meter along-transect interval.

Volumetric erosion analysis: Volumetric erosion calculations were calculated by computing a cell-by-cell difference between the 2020 digital elevation model (DEM) and the 2004 DEM. The total erosion volume was computed by summing measurements (multiplied by cell area) only within a polygon representing the actively eroding area, i.e. the bluff. Uncertainty analysis was performed using a spatially stationary +/- 0.2 vertical uncertainty value.

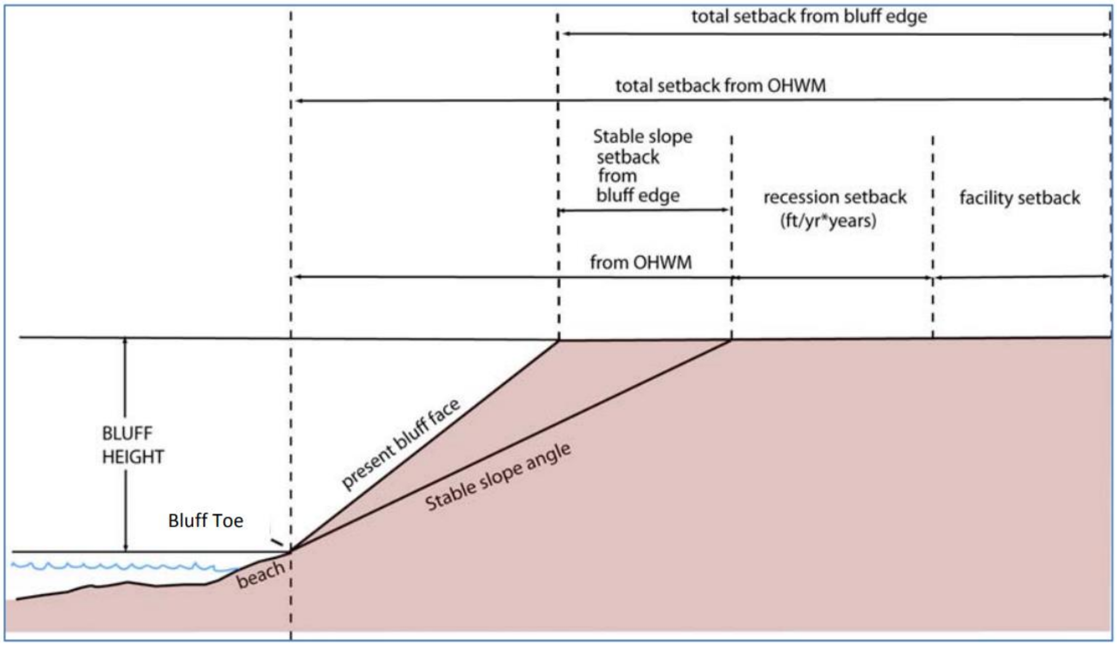


Figure 1. Illustration of coastal setback distance components (Luloff & Keillor, 2015).

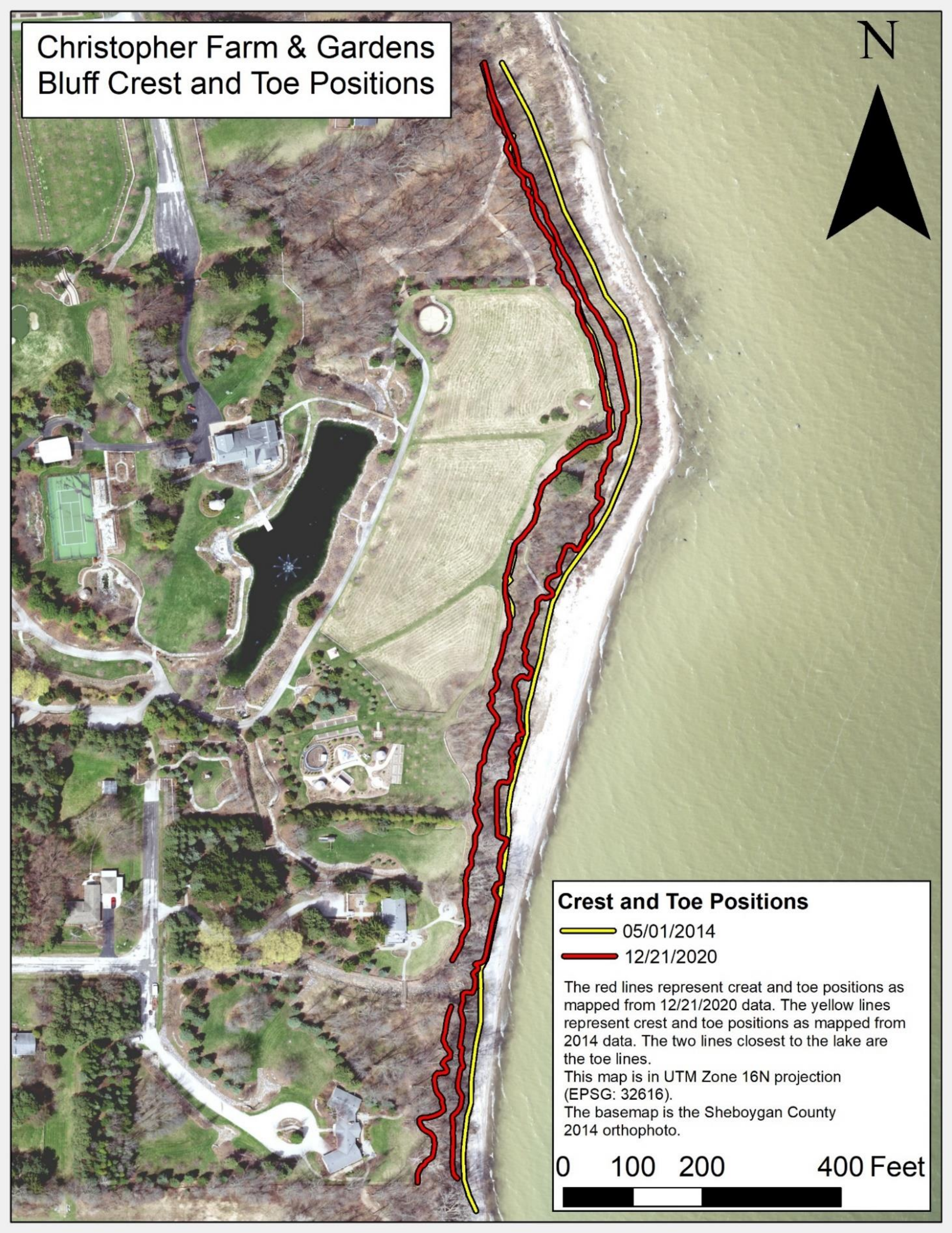
Setback calculations: Using these measurements along with historical recession observations and regional engineering standards, we calculated setback distances following a stable slope angle + recession rate approach (Luloff & Keillor, 2015). This method of setback calculation represents the sum of two setback components, the stable slope angle component and the recession component. The stable slope angle component represents the crest recession required to achieve a ‘stable’ slope angle. This setback component was computed by projecting the crest distance from the toe assuming a stable slope angle of 18.5 degrees. The current crest to toe distance was subtracted from this ‘stable crest distance’ to generate a setback distance from the present bluff crest. This is a conservatively low slope angle that has been previously applied in Wisconsin coastal settings (Luloff & Keillor, 2015). A larger stable slope angle would lead to lesser setback distances. The second component of the setback is the long-term recession rate, assumed here to be 1 ft/yr. This recession rate was multiplied by a duration (5, 10, and 20 years) to generate a distance. The stable slope angle and long-term recession components were added together to generate the three setback distances. An additional component, termed a facility setback, is often added to the other setback components to represent the tolerable operating distance between a piece of infrastructure and the bluff crest (Figure 1).

Results

The mapped crest and toe positions are displayed in Figure 2. We found average 2014-2020 crest recession distances of 0.2±0.5 ft and toe recession distances of 20±10 ft. The numbers following the ± represent the standard deviation of the measurements. For the crest measurements, this indicates that a few areas have experienced relatively small crest recession, but most of the investigated reach has not experienced crest recession. By contrast, most of the bluff toe has experienced significant recession. The northwest oriented shoreline towards the northern half of the reach has experienced the largest magnitude toe recession, likely due to its optimal orientation for the dominant wave direction. These recession distances are equivalent to crest recession rates of 0.0±0.1 ft/yr and toe recession rates of 3.0±1.5 ft/yr. Average bluff recession rates in this general region as reported by Mickelson et al., 1977 are 1-2 ft/yr. These measurements agree with the long-term ~1 ft/yr recession rates reported by Volpano et al., 2020 for a reach just north of this one.

The average measured height of the bluff along this reach in 2020 was 28.5±5.2 ft. The average slope angle of the bluff in 2004 was 15±3 degrees. In 2020, the average slope angle was 27±7 degrees. This represents an ~12 degree steepening of the bluff. It was difficult to delineate the toe of the bluff in the 2014 imagery, which may have led to an underestimate of the 2004 bluff angle. Figure 3 displays select profiles along the bluff that illustrate this steepening. Crest recession between 2004 and 2020 is visible in some of these profiles. The measured volume of material eroded from the bluff between 2004 and 2020 was 30,000±1700 yd^3. The elevation differences between 2004 and 2020 are displayed in Figure 4.

The mean crest recession distance required to achieve a stable slope angle of 18.5 degrees was 26 ft. 5, 10, or 20 feet was added to this to generate the three setback distances (Figure 5). We assumed a spatially homogenous setback distance, meaning that we did not account for differences in the angle of the bluff or recession rates that might occur along the reach. Additionally, the setback distance was applied solely in the E-W direction, rather than explicitly perpendicular to the local shoreline orientation at every point.



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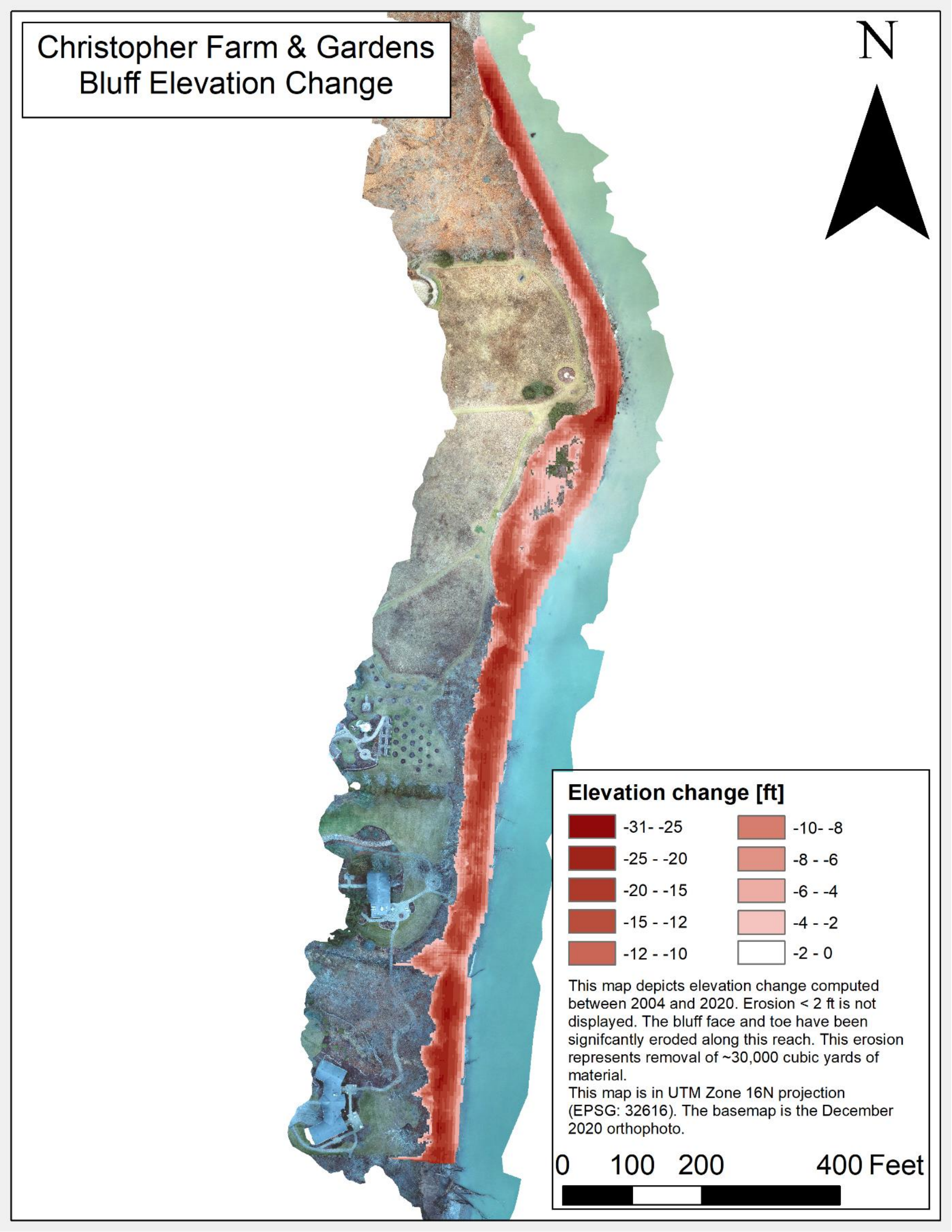
Bluff Crest and Toe Positions

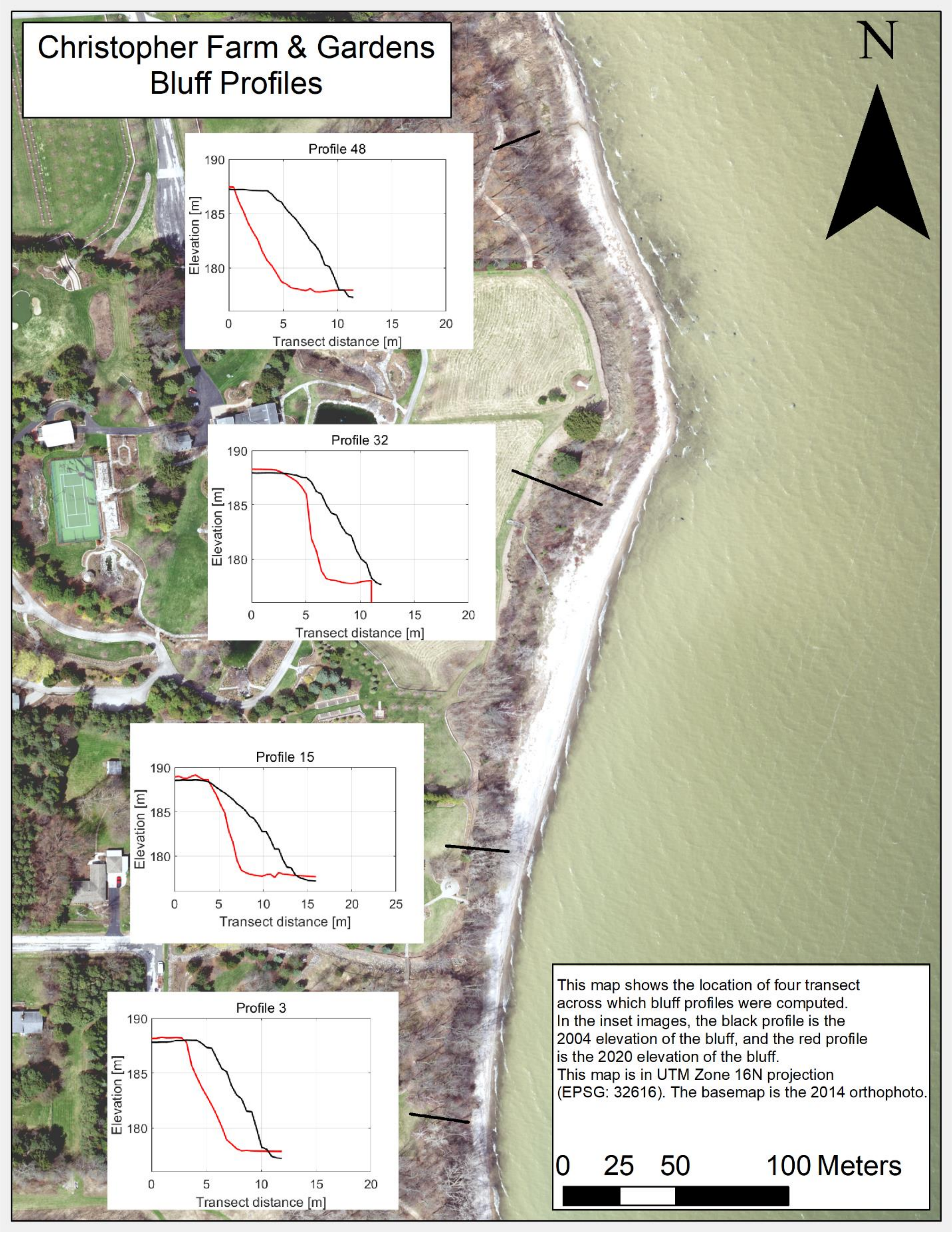
The red lines represent creat and toe positions as mapped from 12/21/2020 data. The yellow lines represent crest and toe positions as mapped from 2014 data. The two lines closest to the lake are the toe lines.
This map is in UTM Zone 16N projection (EPSG: 32616).
The basemap is the Sheboygan County 2014 orthophoto.

Figure 2. Crest and toe positions for the investigated reach as digitized from 2014 and 2020 data.



This map depicts elevation change computed between 2004 and 2020. Erosion < 2 ft is not displayed. The bluff face and toe have been signifcantly eroded along this reach. This erosion represents removal of ~30,000 cubic yards of material.
This map is in UTM Zone 16N projection (EPSG: 32616). The basemap is the December 2020 orthophoto.

Figure 3. Elevation differences (erosion) between 2004 and 2020.



This map shows the location of four transect across which bluff profiles were computed. In the inset images, the black profile is the 2004 elevation of the bluff, and the red profile is the 2020 elevation of the bluff. This map is in UTM Zone 16N projection (EPSG: 32616). The basemap is the 2014 orthophoto.

Figure 4. Select bluff profiles displaying bluff elevation in 2004 (black line) and 2020 (red line).

Figure 5. Bluff setback distances displaying potential setbacks for 5, 10, and 20 year infrastructure.

Conclusions

Forecasting bluff retreat is a difficult and potentially impossible task given the extreme temporal heterogeneity in forces that erode bluffs and the spatial heterogeneity in bluff strength properties. A common approach to land-use planning in the face of this uncertainty is a setback approach that incorporates both long-term recession and stable slope angle components. We have acquired and analyzed high resolution topography to quantify recession and erosion magnitudes along this reach. Significant toe recession has occurred which has not yet propagated to the bluff crest. We have calculated setback distances assuming a stable slope angle of 18.5 degrees and long-term recession rates of 1 ft/yr. These setbacks do not include a 'facility' component, that would account for the tolerable distance between a piece of infrastructure and the bluff crest.

In addition to this report, we are sharing the shoreline (toe and crest) vectors, setback distance vectors, orthophoto, DEM, hillshade, and pointcloud generated during this analysis.

References

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Mickelson, D.M., Acomb, L., Brouwer, N., Edil, T., Fricke, C., & B. Haas, D. Hadley, C. Hess, R. Klauk, N. Lasca, A. F. S. (1977). *Shoreline erosion and bluff stability along Lake Michigan and Lake Superior shorelines of Wisconsin*. Retrieved from Wisconsin Geological Natural History Survey website: https://search.library.wisc.edu/catalog/999498908102121

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Volpano, C. A., Zoet, L. K., Rawling, J. E., Theuerkauf, E. J., & Krueger, R. (2020). Three-dimensional bluff evolution in response to seasonal fluctuations in Great Lakes water levels. *Journal of Great Lakes Research*. https://doi.org/10.1016/j.jglr.2020.08.017

Resources

Peer-reviewed journal articles

Krueger, R., Zoet, L. K., & Rawling III, J. E. (2020). Coastal Bluff Evolution in Response to a Rapid Rise in Surface Water Level. *Journal of Geophysical Research: Earth Surface*, *125*(10), e2019JF005428. https://doi.org/10.1029/2019JF005428

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Sea Grant publications

Living on the Coast: Protecting Investments in Shore Property on the Great Lakes - https://publications.aqua.wisc.edu/product/living-on-the-coast-protecting-investments-in-shore-property-on-the-great-lakes/

When Your Home is at Imminent Risk from Bluff Failure –

https://publications.aqua.wisc.edu/product/when-your-home-is-at-imminent-risk-from-bluff-failure/

Stabilizing Coastal Slopes on the Great Lakes - https://publications.aqua.wisc.edu/product/stabilizing-coastal-slopes-on-the-great-lakes/

Great Lakes Coastal Shore Protection Structures and Their Effects on Coastal Processes - https://publications.aqua.wisc.edu/product/great-lakes-coastal-shore-protection-structures-and-their-effects-on-coastal-processes/

Coastal Processes Manual –

https://publications.aqua.wisc.edu/product/coastal-processes-manual/