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Structure from motion will revolutionize analyses of tidal wetland landscapes

M. Kalacska [a,*], G.L. Chmura [a], O. Lucanus [b], D. Bérubé [c], J.P. Arroyo-Mora [d]

[a] *Department of Geography, McGill University, 805 Sherbrooke St W, Montreal, QC, Canada*
[b] *BelowWater Pictures, Rigaud, QC, Canada*
[c] *Department of Energy and Resource Development, Geological Surveys Branch, NB, Canada*
[d] *Flight Research Laboratory, National Research Council of Canada, Ottawa, ON, Canada*

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ABSTRACT

Ecosystem services of tidal wetlands depend upon hydrology and vegetation, which in turn vary with elevation differences on the order of centimeters. Variability on such a fine scale is not captured in digital elevation models prepared from conventionally acquired LiDAR data products that generally have a spatial resolution of 0.5–1.0 m and vertical uncertainties up to 15 cm. Until recently, capturing critical fine scale features required laborious, hands-on field surveys that took days to collect data and time limitations usually required surveys to be restricted to selected areas of a wetland. Using Structure-from-motion (SfM) photogrammetry and a small unmanned aerial vehicle, precise three-dimensional point clouds, digital surface models (DSM) and color orthomosaics were produced for three salt marshes in Eastern Canada. Vertical and horizontal measurements from the SfM photogrammetry compared favorably to those taken with a Differential Global Positioning System DGPS). Average horizontal displacements of 1.0–2.9 cm were found across the three salt marshes with an average elevation difference of 2.7 cm (±1.7 cm) in comparison to DGPS. Analysis of the relationship of elevation between points taken with the DGPS and extracted from the SfM DSM gave an R^2 of 0.99. With a ground sampling distance of 2.3 cm our SfM photogrammetry generated models captured variations in topography associated with geomorphic features such as creeks, ponds, channel edges, and logs not visible in the DSM prepared from LiDAR of the same sites. SfM photogrammetry enables mapping of important hydrological features, such as creeks carrying drainage from upland watersheds or connectivity of ponds on the wetland surface. The former are important for transport of contaminants or diadromous fish, and the latter is important for resident fish, water birds, and mosquito larvae. Using SfM to distinguish vegetation structure that may indicate vegetation composition will enable more informed analyses of elevational controls on plant distribution and better prediction of their fate with sea level rise.

1. Introduction

Salt marshes provide a variety of ecosystem services, but coastal development has resulted in extensive loss of this ecosystem on most of the world's coastlines (Weis et al., 2016). Those marshes remaining are threatened by accelerated rates of sea-level rise that are accompanying global warming (FitzGerald et al., 2008; Nicholls et al., 1999). Assessing the future of salt marsh ability to continue to provide these ecosystem services (e.g., Chmura, 2013) or success of marsh recovery after remediation of disturbances requires mapping of the features that are critical in the marsh functions required to provide the valuable ecosystems services (e.g., Bowron et al., 2011). However, this mapping is challenging because of the fine vertical and horizontal scale of features.

In tidal salt marshes there is significant variation in biophysical conditions, thus plant growth and productivity vary with small differences in elevation – on the order of centimeters. With decreasing elevations, the hydroperiod (frequency and duration of tidal flooding) increases, resulting in more saturated soils with lower elevation. There is a limited pool of plant species that have evolved strategies to deal with the stresses posed by flooded, saline soils. Thus, marshes have fairly low diversity and the species that dominate the marsh are largely distributed along the gradient in frequency of tidal flooding with respect to their ability to tolerate stress – a gradient predictable from surface elevation. On a Wadden Sea tidal marsh some dominant graminoids have elevation ranges that span <50 cm (Bockelmann et al., 2002). On the Adriatic Sea graminoid dominance can shift with elevation changes of <10 cm (Silvestri et al., 2005). Porter et al. (2015) report that *Spartina*

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* Corresponding author.
E-mail address: margaret.kalacska@mcgill.ca (M. Kalacska).

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alterniflora in a salt marsh on Nova Scotia's (Canada) Atlantic coast has an elevation range of 12 cm while the range of *Juncus balticus* is as small as 11 cm on the Nova Scotia coast of the Gulf of St. Lawrence. Small changes in elevation or height of tidal flooding also affect plant productivity, thus plant survival, their contribution to soil organic matter, and ultimately the marsh surviving sea level rise (FitzGerald et al., 2008). Studies of production of the dominant grass *S. alterniflora* on the coasts of Massachusetts and North Carolina (USA) have revealed that it is highly sensitive to the level of mean high water, which varies over the 18.6 yr lunar nodal cycle, but has also increased over the longer term (Morris et al., 2013). On the Massachusetts coast an increase of 10 cm in the level of mean high water can increase productivity of *S. alterniflora* by 25%. Experiments on the coast of North Carolina have shown that the upper and lower limit of *S. alterniflora* spans a ~1.6 m range in elevation with optimal growth near the mid-range.

Hydrological features critical to marsh functions have been documented with aerial photographs. However, marsh functions that provide habitat and support secondary production of fish and wildlife depend upon channel networks and systems of surface ponds (e.g., Erwin et al., 1991; Kneib and Wagner, 1994; Kneib, 1987; Trocki and Paton, 2006; Larkin et al., 2008; MacKenzie and Dionne, 2008; Johnston and Sheaves, 2008), Many features are often too small to detect from photos taken on standard flights (e.g., MacDonald et al., 2010) and contracting specialized low altitude flights is generally cost prohibitive. The alternative is to map features using Differential Global Positioning System (DGPS), requiring tens of thousands of survey points to adequately map some study areas (e.g., Chassereau et al., 2011; MacDonald et al., 2010). The terrain of salt marshes, which includes soft sediment, ponds, and channels, hinders access by foot to all marsh areas (Madden et al., 2015). Some marsh habitats are sensitive to extensive foot traffic, which can disturb nesting birds or trample invertebrates such as the larvae of the endangered Maritime Ringlet Butterfly (*Coenonympha nipisiquit*) that live within the plant litter. DGPS surveys can also be hindered by trees growing in the terrestrial areas surrounding marshes if their canopies interfere with the GPS signal (Naesset and Jonmeister, 2002).

Marsh elevations can be measured with a digital elevation model (DEM) developed from DGPS or conventional surveying, but these methods are too time consuming and labor intensive to acquire data across large areas (Lohani and Mason, 2001). A commonly used alternative is to develop a DEM from discrete return (Mathew et al., 2010; Bowron et al., 2011; Millard et al., 2013; Krolik-Root et al., 2015; Kulawardhana et al., 2015; Stammermann and Piasecki, 2014) or full waveform LiDAR data (Rogers et al., 2015). Though not yet as common, LiDAR data have also been collected from an unmanned aerial vehicle (UAV) platform in other environments, primarily for tree canopy structure analyses (Wallace et al., 2016). We differentiate between two types of DEMs, digital surface models (DSM) which include objects such as trees and buildings as part of the model and digital terrain models (DTM) which represent the bare earth elevation. The cost of airborne LiDAR is prohibitive; in many cases data have been collected with multiple uses intended. It has not been flown along all North American coasts, and where it has, may not be publically available (Chmura, 2013). Although LiDAR reflects elevations on the order of centimeters, the coarse horizontal resolution (e.g., 0.5–1 m) of the gridded DSM/DTM products means that some critical features such as channels, small ponds, and narrow vegetation zones will not be visible. Finer spatial resolution (e.g. 10 cm) gridded products are available for a few locations, but are less common than the coarser resolution ones.

In this study we compare the utility of LiDAR, aerial photographs and Structure from Motion (SfM) photogrammetry products for revealing critical features in three salt marshes on the New Brunswick coast of the Gulf of St. Lawrence. As described below, in a strict sense our study combines both SfM and multi-view stereo (MVS) photogrammetry, but is referred to as SfM for brevity. Although other platforms have been used to collect low elevation photographs we used a quadcopter (a UAV propelled by four rotors) because it was suited to the salt marshes in our study area. Blimps (Guichard et al., 2000) and kites (Bryson et al., 2013; White and Madsen, 2016) have been used successfully, but they require guidance by walking – something not possible when public roads and private property border the wetland, while UAVs can be carefully guided from a single location. In salt marshes, treacherous terrain (e.g. wide creeks, ponds and deep mud) and sensitive habitat also make these other platforms impractical.

While the concept of SfM photogrammetry was developed nearly 40 years ago (Ullman, 1979), the increase in performance of personal computers/workstations and the availability of reliable and affordable UAVs with high quality camera systems has rapidly increased its application in geomatics and mapping (Fonstad et al., 2013; Gomez et al., 2015). The purpose of SfM is the reconstruction of a 3D point cloud from overlapping 2D photographs (Gomez et al., 2015). SfM is scale invariant (James and Robson, 2012) and the output is only limited by the camera resolution (Gomez et al., 2015). The algorithms commonly used for SfM originated in the machine vision community. The premise is to locate common points across several 2D photographs taken from different viewing angles/positions and reconstruct the object/scene in 3D (Ferreira et al., 2017). Conventional DEM derivation from aerial photograph stereo-pairs is limited by restrictive practical requirements for the photographs such as the need for known coordinates on observable control points (James and Robson, 2012). Contrarily, SfM algorithms were originally developed to create 3D models of objects from unordered photographs (Snavely et al., 2006). SfM algorithms recover the camera parameters, pose estimates (i.e. position and orientation) from the photographs and recreate 3D versions of the object or surface, thus providing more flexibility than conventional photogrammetry from stereo-pairs (Snavely et al., 2006). There are several implementations of SfM, an overview of the strengths and weaknesses of different algorithms used for multi-image SfM is discussed by Oliensis (2000) and Smith et al. (2016).

A critical aspect of SfM is the estimation of distinctive scale invariant features (points of commonality) of the object or scene across several images from different viewpoints. Several implementations are based on variations of the Scale-Invariant Feature Transform (SIFT) algorithm (Lowe, 2004), which is widely used in machine vision as the critical first step in generating a 3D point cloud (Smith et al., 2016). There are a number of steps required to employ SIFT. The first requires locating distinctive key points (i.e. invariant features) through a space-scale extrema (maxima and minima) detection using a difference of Gaussians function. The second step involves improving the set of candidate key points to retain the true location of the extrema by fitting a model for location, scale, and ratio of principal curvatures. Filtering is then used to reject points with low contrast and those with a strong edge response. In the third step the remaining key points are assigned an orientation to remove effects of image rotation and scale (e.g. photographs taken from different distances). The retained key points are robust to varying illumination conditions, view angle, pixel noise, etc. Next, descriptors of the local image region for each key point are calculated from the histograms of the orientations. Local gradients rather than sample intensities are used to create descriptors of each key point resulting in 128 dimension feature vectors. Following the application of a version of SIFT, in geomatics it is common for the workflow to proceed with the implementation of a Multi-View Stereo (MVS) photogrammetry algorithm to increase the density of the 3D point cloud (Strecha et al., 2008; Shao et al., 2016; Smith et al., 2016). Lastly, to improve the usability of the digital surface models, an interpolation is used to create a raster DTM. A critical aspect that differentiates the use of SfM for geomatics applications (i.e. DTM creation) as opposed to 3D object reconstruction is the necessity to locate the products according to vertical and horizontal coordinate systems, therefore, the generated 3D point clouds and products such as the raster DTMs need to be georeferenced (James and Robson, 2012).