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The Tidal Marsh Inundation Index (TMII): An inundation filter to flag flooded pixels and improve MODIS tidal marsh vegetation time-series analysis

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ABSTRACT

Remote sensing in tidal marshes can provide regional assessments of wetland extent, phenology, primary production, and carbon sequestration. However, periodic tidal flooding reduces spectral reflectance, especially in the near and short-wave infrared wavelengths. Consequently, marsh vegetation time-series products that lack tidal filtering, such as those provided by MODIS (Moderate Resolution Imaging Spectroradiometer), may not reflect true vegetation trends. We created a new Tidal Marsh Inundation Index (TMII) for processing daily 500-m MODIS surface reflectance data and calibrated it with a *Spartina alterniflora* salt marsh pixel on Sapelo Island, GA. Ground-truth data for TMII was extracted from a PhenoCam, which collected high frequency digital photography of the TMII calibration pixel. To identify the best wavelengths to include in the TMII, we compared goodness of fit metrics from generalized linear models (GLMs). Predictors for these GLMs included suites of normalized difference indices from the literature as well as other band combinations. We also explored including a phenology parameter that could scale TMII relative to vegetation development. Ultimately, TMII was based on the normalized difference of green and shortwave infrared reflectance in combination with a phenology parameter composed of the moving average of the normalized difference of near infrared and shortwave infrared reflectance. This final index allowed a single optimized decision boundary to identify flooding across the annual growth cycle. When compared to ground-truth data from the PhenoCam, the TMII classified flooded conditions with 67–82% and dry conditions with 75–81% accuracy, respectively, across training, testing and validation datasets. We applied TMII to new *S. alterniflora* marsh MODIS pixels on Sapelo Island, GA as well as on Plum Island, MA. For these new pixels, TMII classified marsh flooding with 77–80% overall accuracy. We also demonstrated how users can apply TMII filtering in a MODIS workflow to create vegetation time-series composites within *S. alterniflora*, *Spartina patens* and *Juncus roemerianus* marshes. We showed how a new user can validate and optimize TMII in their application, either by comparing it to inundation data or by validating the filtered vegetation time series against field data. We also compared TMII-filtered composites to the existing MODIS MOD13 16-d Normalized Difference Vegetation Index (NDVI) product. TMII-filtered composites generated less noisy time-series that fit field data better than MOD13. TMII filtering was most important on Sapelo Island, where the tide range was high and vegetation was sparse. Results were less dramatic when TMII was applied to different marsh species within the Gulf Coast sites with lower tidal ranges, but TMII-filtering still improved vegetation time series. Thus, preprocessing MODIS imagery with the TMII effectively identified most inundated pixels. The TMII represents a step forward for wetland remote sensing that will be useful for improved estimation of phenology, biomass and carbon storage in coastal marshes.

Abbreviations: AUC, Area Under the Curve; GLM, generalized linear model; EVI, enhanced vegetation index; fPAR, fractional photosynthetically active radiation; GCE-LTER, Georgia Coastal Ecosystems Long Term Ecological Research; GPP, gross primary productivity; LAI, leaf area index; MODIS, Moderate Resolution Imagery Spectroradiometer; NASA, National Aeronautics and Space Administration; NERR, National Estuarine Research Reserve; NIR, near-infrared; NPP, net primary productivity; NDVI, Normalized Difference Vegetation Index; NDWI, Normalized Difference Water Index; PLS-DA, Partial Least Squares Discriminant Analysis; PIE-LTER, Plum Island Ecosystems Long Term Ecological Research; ROC, Receiver Operating Characteristic; SWIR, short-wave infrared; TMII, Tidal Marsh Inundation Index; WDRVI, Wide Dynamic Range Vegetation Index; VIS, visible; VARI, Visible Atmospheric Resistant Index

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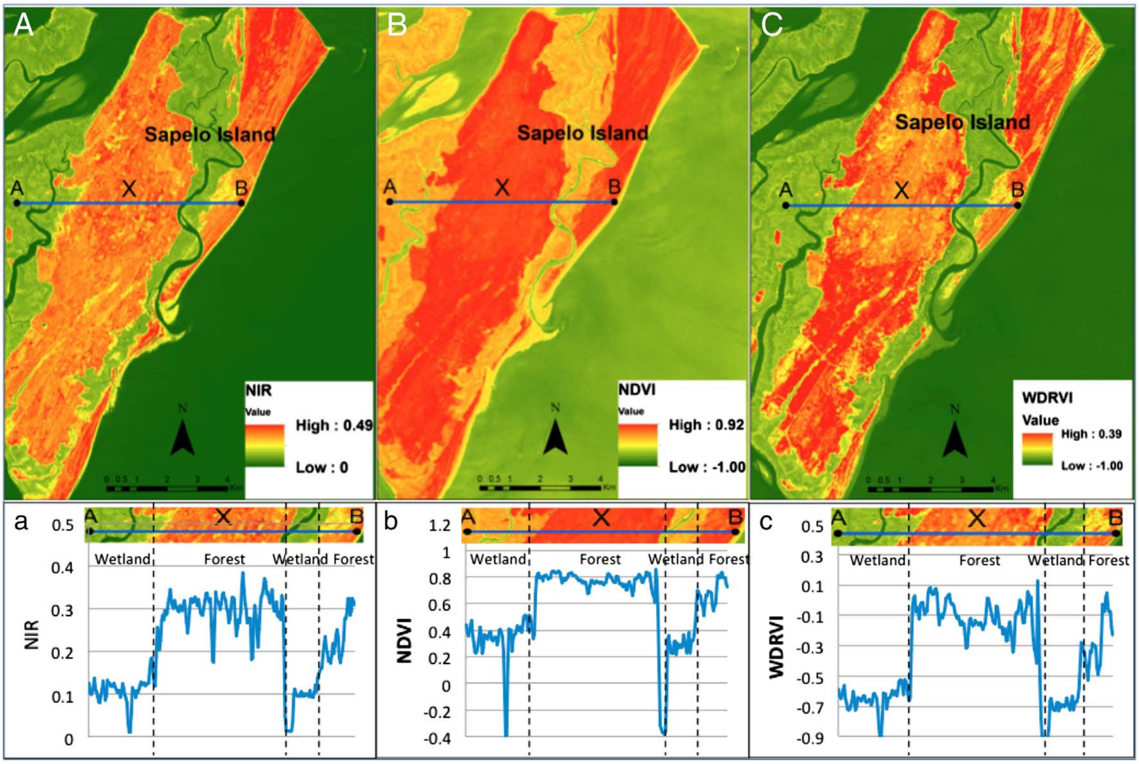

Fig. 1. Spatial patterns of NIR surface reflectance (A), NDVI (B), and WDRVI (C) across Sapelo Island, Georgia, USA. Lower panels (a–c) depict these same variables across a west-east transect and show a spectral reflectance depression in wetlands resulting from soil background moisture.

1. Introduction

Remote sensing can provide landscape-level analysis of vegetation dynamics (Goetz et al., 2009), aiding in broad-scale modeling of phenology, primary production and climate change effects (Mishra and Ghosh, 2015; Turner et al., 2004). In coastal marshes particularly, vegetation helps contribute to “blue carbon” in soils through both autochthonous production and sediment trapping (Mcleod et al., 2011), and remote monitoring can help quantify the carbon sequestration potential of these systems (Byrd et al., 2014; Stralberg et al., 2011). However, remote sensing in coastal marshes is complicated by periodic tidal flooding, which dampens spectral reflectance (Cho et al., 2008) and introduces noise that obscures the shape and magnitude of vegetation patterns. Such noise results from water and moist soil, which differentially attenuate the intensity of visible (VIS), near-infrared (NIR) and short-wave infrared (SWIR) spectra (Kearney et al., 2009; Mishra et al., 2012, 2015; Turpie, 2013). Consequently, vegetation time-series based on traditional vegetation indices, such as the Normalized Difference Vegetation Index (NDVI) or the Wide Dynamic Range Vegetation Index (WDRVI) have a reduced red-NIR contrast and a lower overall range compared to terrestrial systems (Fig. 1). As a result, tidal effects can decouple vegetation indices from vegetation patterns (Cho et al., 2008). An inundation index is therefore needed to identify flooded observations so we can use remote sensing to effectively model true tidal marsh vegetation dynamics.

In order to separate water from other land-uses, researchers generally apply one of a suite of normalized difference water indices (NDWI); for a review see Ji et al. (2009). These NDWI-type indices are successful at mapping water bodies (Ji et al., 2009) and the best indices for mapping are those with similar index values for vegetation and soil (Ji et al., 2009). Optimization of thresholds for NDWI-type indices have generally been established with data from a single, short time period and were most successful at discriminating pixels with 100% water cover (Ji et al., 2009). We found these indices were less accurate for mapping periodic tidal inundation across multi-temporal vegetated marsh datasets. As the annual cycle progresses, the relative difference between water and vegetation also changes, requiring an index that accounts for seasonal phenology.

We built on the existing NDWI indices to create an optimized index for pre-processing MODIS (Moderate Resolution Imaging Spectroradiometer) satellite data in tidal marshes. Our goal was to develop an index that makes filtering flooded pixels from multispectral remote sensing data straightforward. We focused our efforts on the MODIS sensor, curated by NASA (the National Aeronautics and Space Administration). We used MODIS because it is freely available, has global coverage, a 1 day return frequency, and provides many useful products (modis.gsfc.nasa.gov), making this platform popular for broad-scale vegetation analysis. The daily 500-m MODIS surface reflectance product (MOD09GA) is especially useful along coasts, where frequent cloud cover interferes with space-to-ground spectral detection. Although MODIS surface reflectance-derived products are widely used in terrestrial systems, they are often inaccurate within tidal marshes because current compositing algorithms do not account for tidal flooding (Huete et al., 1999). These existing products include MOD15 (the leaf area index (LAI) and fractional photosynthetically active radiation (fPAR) product), MOD13 (NDVI and enhanced vegetation index (EVI) product), and MOD17 (the net and gross primary productivity product (NPP/GPP). This also means that independent wetland productivity models relying on these products as input data suffer from tidal fluctuation uncertainty (Barr et al., 2013). Additionally, studies that use raw surface reflectance for habitat mapping and vegetation dynamics are often forced to resort to complex and tedious procedures to filter inundated pixels (Knight et al., 2006; O'Donnell and Schalles, 2016; Wang et al., 2012).

In this paper, we describe the development and application of a new index for pre-processing MODIS data in coastal marshes, which we call the Tidal Marsh Inundation Index (TMII). We calibrated and validated the TMII using ground-truth data from a tidal *Spartina alterniflora* salt marsh located in Sapelo Island, GA, USA. We then applied the optimized TMII to two additional *S. alterniflora* MODIS pixels on Sapelo