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# Remote Detection of Disturbance from Motorized Vehicle Use in Appalachian Wetlands

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## ABSTRACT

Wetland disturbance from motorized vehicle use is a growing concern across the Appalachian coalfields of southwestern Virginia and portions of adjacent states, particularly as both extractive industries and outdoor recreation development expand in regional communities. However, few attempts have been made in this region or elsewhere to adapt approaches that can assist researchers and land managers in remotely identifying and monitoring wetland habitats disturbed by motorized vehicle use. A comparative analysis of wetlands impacted and unimpacted by off-road vehicle activity at a public recreation area in Tazewell County, Virginia was conducted to determine if and how a common, satellite-derived index of vegetation health, normalized difference vegetation index (NDVI), can remotely detect wetland disturbance. NDVI values were consistently lower in wetlands impacted by several years of off-road vehicle use when compared to adjacent, unimpacted sites, with statistically-significant NDVI coldspots growing in size in impacted wetlands across the same time period. While considerations exist related to the resolution of data sources and the identification of specific modes of disturbance, NDVI and associated spatial analysis tools may provide a simple and cost-effective way for researchers and land managers to remotely monitor rates of wetland disturbance across mountainous portions of the eastern United States.

**Key Words:** NDVI, vegetation, off-road vehicle, disturbance, wetland

## INTRODUCTION

The coalfields of the central Appalachian Mountains, located across southwestern Virginia, eastern Kentucky, southern West Virginia, and eastern Tennessee, have historically been one of the most heavily-impacted areas of the eastern United States in terms of anthropogenic disturbances. More than 3000 $km^2$ of this region have been altered due to surface mineral extraction, with extensive timber harvesting and gas well development occurring across the same region (Saylor 2008; Townsend et al. 2009; Miller and Zegre 2016; Ross et al. 2016). Past work has found these activities to exert significant ecological pressures on ecosystems across the Appalachian coalfields, including reduced habitat availability and altered community composition for bird, herpetofauna, and plant taxa, as well as changes to water quality and nutrient cycling in regional waterways (Petty et al. 2013; Wickham et al. 2013; Maigret et al. 2019).

Wetland ecosystems are of particular concern within the central Appalachian coalfields. The overall extent and number of wetland habitats is lower in this region compared to other Appalachian physiographic provinces due to steep terrain that constrains wetland formation mostly to floodplain areas along rivers and larger streams, as well as midslope seepages near the headwaters of smaller streams (Thompson et al. 2007; Fleming and Patterson 2017). As a result, wetlands in this region are typically given a high conservation value and are a management priority within regional protected areas (USDA Forest Service 2004; Thompson et al. 2012; Weber and Bulluck 2014).

Wetlands and waterways across the central Appalachian region have faced disturbance risks from the aforementioned forms of natural resource extraction, including altered water chemistry and quality (Kiviat 2013; Cook et al. 2015), altered soil dynamics (Stephens et al. 2015), and the introduction of non-native taxa into wetland vegetation assemblages (Balcombe et al. 2005). However, ongoing socioeconomic shifts across the region are resulting in a decrease in surface mining and related forms of disturbance and a corresponding increase in recreational development across large parcels of private and public land formerly used for resource extraction (Frisch and Johanssen 2014; Scott et al. 2017). In particular, the development of off-road vehicle trail systems is a growing economic development strategy being employed by local and state governments, with more than 1500 km of motorized trails developed across southwestern Virginia, southern West Virginia, eastern Kentucky, and eastern Tennessee (Hackbert and Lin 2009; Scott 2010).

Wetland ecosystems worldwide are often targeted for motorized trail development or otherwise impacted by off-road use (Meyer 2002; Arp and Simmons 2012). These activities have been shown in past work to decrease vegetation biomass and productivity in some wetland habitats (Hannaford and Resh 1999; Welch et al. 2002) and alter the composition of some wetland vegetation assemblages (Taylor and Raney 2013). Soil compaction from off-road vehicle use is also of particular concern across multiple habitat types since it can lead to diminished moisture infiltration needed to support plant growth, as well as increased rates of soil erosion (Webb and Wilshire 1983; Liddle 1997; Ouren et al. 2009). Impacts from soil compaction generally increase with the number of vehicle passes at a given site (Iverson et al. 1981; Lovich and Bainbridge 1999), with soil compaction from vehicle use persisting for years following disturbance in some habitat types (Ahlstrand and Racine 1993). Wetlands also exhibit some of the highest susceptibility to trail-related erosion and soil scouring when compared to dry forested sites and other terrestrial habitats (Sobczak and Pernas 2002; Trip and Wiersma 2015). These impacts have cumulatively led many trail planning programs to recommend wetland avoidance during motorized trail development to minimize environmental impacts (Snyder et al. 2008). In spite of these concerns, few attempts have been made to gauge the extent of wetland disturbance and other environmental impacts due to motorized trail development across the central Appalachian region, where trail networks are expanding at an increasing rate (Sharp et al. 2020). This lack of an ability to detect and monitor wetland disturbance from off-road vehicle use at the landscape scale currently precludes such assessments, as well as the development of studies examining the ecological impacts of such activities and the design of appropriate mitigation measures.

Remote sensing approaches hold promise as one avenue for both researchers and land managers to identify wetlands damaged by off-road vehicle use and other anthropogenic disturbances. Remotely-sensed imagery, for example, can both highlight the location of wetland habitats within the surrounding landscape matrix (Ozesmi and Bauer 2002; Adam et al. 2010) and identify spatiotemporal changes in wetland characteristics using indices of ecological condition derived from remotely-sensed data (Mayer and Lopez 2011; Hinkel et al. 2017). Such remote sensing approaches and associated metrics have been used to detect signatures of both natural (Rodgers et al. 2009; Potter 2018) and anthropogenic (Kayastha et al. 2012; Alatorre et al. 2016; Jaramillo et al. 2018) disturbances in wetland habitats across a variety of ecosystems. In particular, normalized vegetation difference index (NDVI) data are increasingly being incorporated as a metric of vegetation health that can allow researchers to remotely gauge wetland condition in response to disturbance events (Potter 2018; Wilson and Norman 2018; Taddeo et al. 2019; Vanderhoof et al. 2020). To date, however, these approaches have yet to become adapted for use in detecting signatures of wetland disturbance from motorized vehicle use. The purpose of this study was therefore to test the ability of remotely-sensed datasets to identify wetland disturbance in response to motorized vehicle use, particularly for wetlands impacted by vegetation loss and vehicle scouring, at a site heavily impacted by off-road vehicle trail development in the New River watershed of southwestern Virginia.

## MATERIALS AND METHODS

### Study Area

The focal area of this study encompassed a 20 $km^2$ region along the northern half of the lower Laurel Fork watershed in Tazewell County, Virginia, specifically an area presently maintained as a public off-road vehicle recreation area by Virginia's Southwest Regional Recreation Authority. Habitats across this area are mixed mesophytic forest ecosystems typical of middle and lower elevations within the Cumberland Mountains Physiographic Province, with past surface mining activities originating during the 1970s occurring across portions of the region. Wetlands across the study area are primarily large headwater seepage wetlands, isolated wetlands incidentally formed as a result of past surface mining, and floodplain wetlands along larger streams.

Six wetland areas from the study area were selected for analysis: three wetland areas that have been incorporated as water features along official motorized trails (hereafter "impacted" wetlands) and three wetland areas not associated with (e.g., >0.25 km from) official motorized routes (hereafter "unimpacted" wetlands; Fig. 1). All selected sites were open-canopy wetlands characterized predominantly by emergent vegetation occurring within flat to gently-sloping zones of groundwater discharge along first- or second-order headwater streams. Small and shallow headwater wetlands of this type are common across the Cumberland Mountains where either naturally-occurring terrain or terrain modified by surface mining activities facilitates the pooling of surface runoff and groundwater discharge and the establishment of wetland soils and vegetation (Thompson et al. 2007; Atkinson et al. 2010). All wetlands were of roughly equivalent size (0.5-2.14 ha) and at roughly equivalent elevations (760-790 m asl), and none have experienced any significant anthropogenic disturbance, outside of the off-road vehicle use being investigated in this study, in at least the past five years. Off-road vehicle disturbance was confirmed at all impacted sites via evidence of substantial vehicle scouring (tire rutting of wetland soils, crushed vegetation) along with official trail signage within each wetland area during field visits following the peak recreation season in late September of 2018 and 2019.

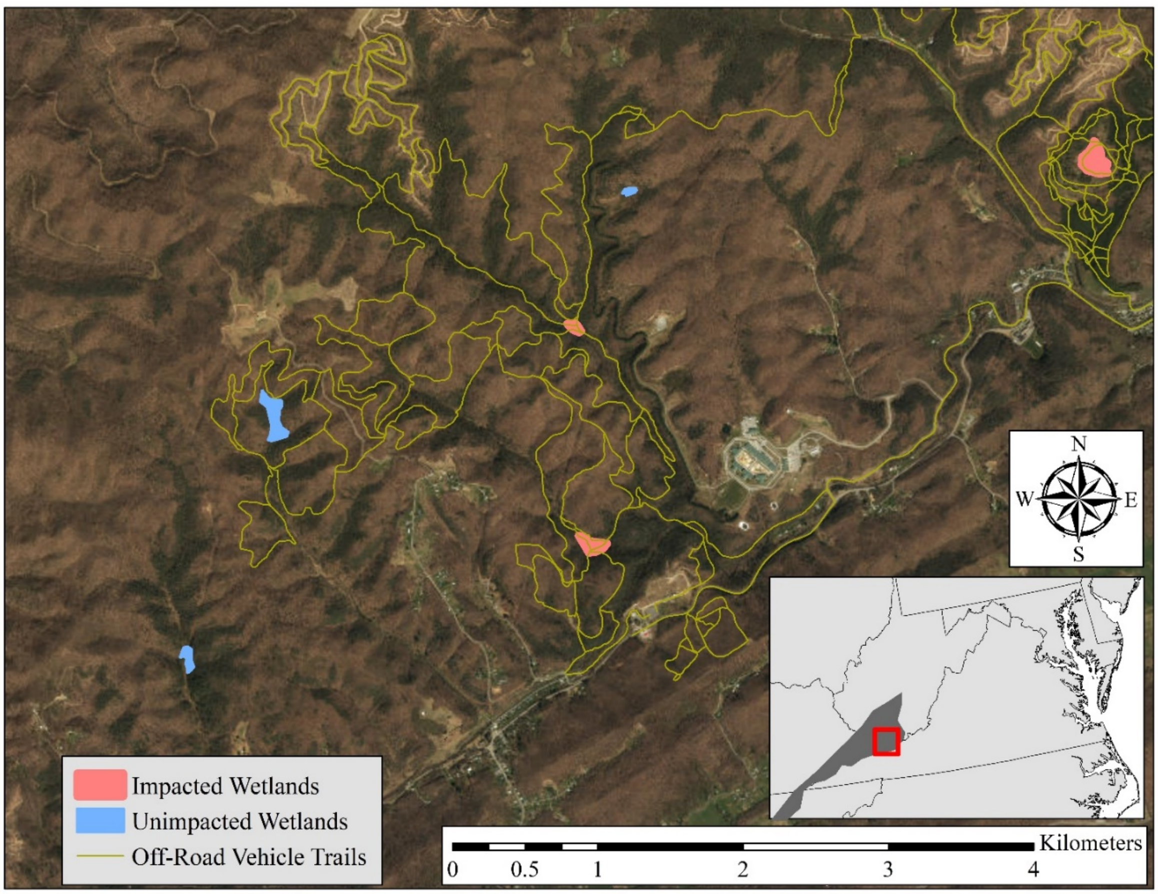



**FIGURE 1**: Focal wetlands at the Original Pocahontas Off-Road Vehicle Trail System in Tazewell County, Virginia. Trail locations were generated from publicly-available GPS data from the trail system's managing agency (http://spearheadtrails.com). Red box in inset map denotes location of the study area, with the shaded region denoting the location of the Cumberland Mountains province along the borders of Virginia, Tennessee, Kentucky, and West Virginia, where rapid off-road vehicle trail development is occurring at the regional scale.

<u>Data Sources</u>

Wetlands impacted by off-road vehicles should exhibit significant differences in remotely-sensed indices of vegetation health, relative to unimpacted wetlands across the same area. To test this, 100 x 100 $km^2$ tiles from publicly-available Sentinel-2 satellite imagery were downloaded. Sentinel-2 imagery is generated across 13 spectral bands that include visible, near infrared, and short-wave infrared spectra at a spatial resolution of 10 m to 60 m (Drusch et al. 2012). Sentinel-2 tiles were downloaded from the United States Geological Survey Earth Resources Observation and Science Center (https://www.usgs.gov/centers/eros).

Specifically, a representative Sentinel-2 tile was chosen covering the study area from each year encompassing a timespan from 2015-2019, corresponding to dates before the full study area's opening to off-road users (2015) and multiple years of imagery following its opening date (2016-2019). An imagery date for each year was selected from the same period within the local dry season (the final two weeks of October) in order to (i) capture wetland condition following the peak summer recreation season and (ii) minimize confounding seasonal differences in vegetation growth, precipitation, and artifacts from standing water. All imagery was additionally recorded prior to the local onset of colder temperatures and significant frost events. Imagery was also selected to minimize cloud cover, with no cloud cover visible across the study area in any of the aforementioned images.

Multispectral bands from Sentinel-2 imagery can be used to calculate indices of ecological condition, specifically those reflecting vegetation health. Sentinel-2 imagery was used to calculate one such index, normalized difference vegetation index (NDVI), which summarizes vegetation health on a 1 to -1 scale (Goward et al. 1991). NDVI was calculated for each year (2015-2019) using the Image Analysis extension in ArcGIS v10.3 as the following:

$$NDVI = \frac{(IR - R)}{(IR + R)}$$

where IR and R refer to pixel values from the 10 m infrared and red Sentinel-2 bands, respectively. Following NDVI calculation, NDVI pixel values were extracted for each year from within each focal wetland for further analysis. Wetland polygons were generated based on wetland extents as identified by the Virginia Wetlands Catalog (Weber and Bulluck 2014) and high-resolution aerial orthoimagery (VGIN 2019).

<u>Statistical Analyses</u>

NDVI data from successive dates can be used to quantify vegetation change across a time series (Piao et al. 2006; Franke and Menz 2007; Zhao et al. 2009). Linear Mixed Effects Models were used to evaluate relationships between NDVI, wetland type (impacted vs. unimpacted), and year, with NDVI as a dependent variable and wetland type and year included as independent variables. Models were constructed using the lmer function in the lme4 package in R.

Specifically, four candidate models were evaluated reflecting the following potential explanatory variables for NDVI patterns as fixed factors: wetland type alone, year alone, an interaction between wetland type and year, and a null model with no fixed factors. Since pixels from the same wetland sites were not independent, site was included as a random factor in all candidate models. Models were evaluated using Akaike's Information Criterion (AIC) via the anova function in the car package in R, with pairwise comparisons between interaction terms (wetland types per year) performed using the emmeans package.

A more informative measure of vegetation change than aggregated decreases in NDVI is that of spatial clustering of low NDVI values. Specifically, statistically-significant clusters of NDVI minima would be expected to be present in wetland areas experiencing disturbance from off-road vehicles, with the size of such clustered minima expanding over time as disturbance continues. The Getis-Ord Gi* statistic (Getis and Ord 1992) was used to assess statistically significant patterns of clustering of high and low NDVI values – or hotspots and coldspots, respectively – across the study area. The Getis-Ord Gi* statistic compares grid cell values to those of neighboring features, assessing the significance of clustered patterns by comparing actual local sums to expected local sums from the same areas. Resulting values can then be grouped into bins representing the degree of statistically-significant clustering across a spatial extent.

Getis-Ord Gi* statistics were calculated for each year's NDVI dataset using the Hot Spot Analysis function in ArcGIS v10.3. Resulting hotspots and coldspots (99% confidence, 95% confidence, and nonsignificant clustering) were visually identified in ArcGIS, with Getis-Ord Gi* statistics exported for each year within each focal wetland polygon.

## RESULTS

Linear mixed effects models indicated that wetland type, year, and an interaction between these two factors were all significant ($\alpha = 0.05$) predictors of NDVI, with the full model (wetland type + year + wetland type x year) being the best model based on AIC values (Table 1). Mean NDVI values were not significantly different between impacted and unimpacted wetlands in 2015 (prior to the full trail system's opening and the onset of vehicle disturbance at impacted sites) or in 2016 (early in the study area's operation as a motorized recreation area); however, mean NDVI values were significantly lower in impacted wetlands when compared to unimpacted wetlands in each year from 2017-2019, following multiple years of motorized use in impacted wetlands (Fig. 2). Differences between impacted and unimpacted wetland types generally increased in the years following the opening of the trail system to motorized users and an increase in vehicle disturbance, with NDVI differences between impacted and unimpacted wetlands more than doubling between 2015 and 2018 (Fig. 3). These patterns match with actual conditions at each impacted site, which contained large and growing areas of crushed vegetation and scoured/compacted soil in wheel ruts (see aerial orthoimagery in Fig. 4), versus unimpacted wetlands lacking these features.

Impacted wetlands were also characterized by significant NDVI coldspots determined via hotspot analyses in ArcGIS v10.3. The proportion of each impacted wetland characterized by statistically-significant clustering of low NDVI values generally increased after the study area was opened to motorized users (Fig. 4), with the size of coldspots within wetland polygons more than doubling from 2015 to 2019 at impacted sites (Table 2). Nearby unimpacted wetlands generally exhibited a lack of increasing coldspot formation, with the proportion of each wetland characterized by statistically-significant clustering of low NDVI values remaining relatively constant from 2015-2019. By contrast, several unimpacted wetlands exhibited increasing levels of hotspot formation, indicating significant clustering of high NDVI values and an improvement in vegetation health.

**TABLE 1**: Linear mixed effects model results for four candidate models explaining NDVI variability in wetlands across the lower Laurel Fork watershed on Virginia's Original Pocahontas Off-Road Trail System. For listed candidate models, "None" refers to the model including no predictor variables, "Type" refers to the model including wetland type (impacted versus unimpacted) only, "Year" refers to the year of imagery only, and "Type*Year" refers to an interaction between year and wetland type. "npar" refers to the number of parameters, "AIC" refers to Akaike's Information Criterion, and "logLik" refers to the log-likelihood value.

| Model | npar | AIC | logLik | Wald $\chi^2$ | P-value |
|---|---|---|---|---|---|
| Type*Year | 5 | 14146 | -7068.0 | 5.0978 | 0.02 |
| Year | 4 | 14149 | -7070.6 | 15.1867 | <0.0001 |
| Type | 4 | 14164 | -7078.2 | 5.0992 | 0.02 |
| None | 3 | 14167 | -7080.7 | n.a. | n.a. |

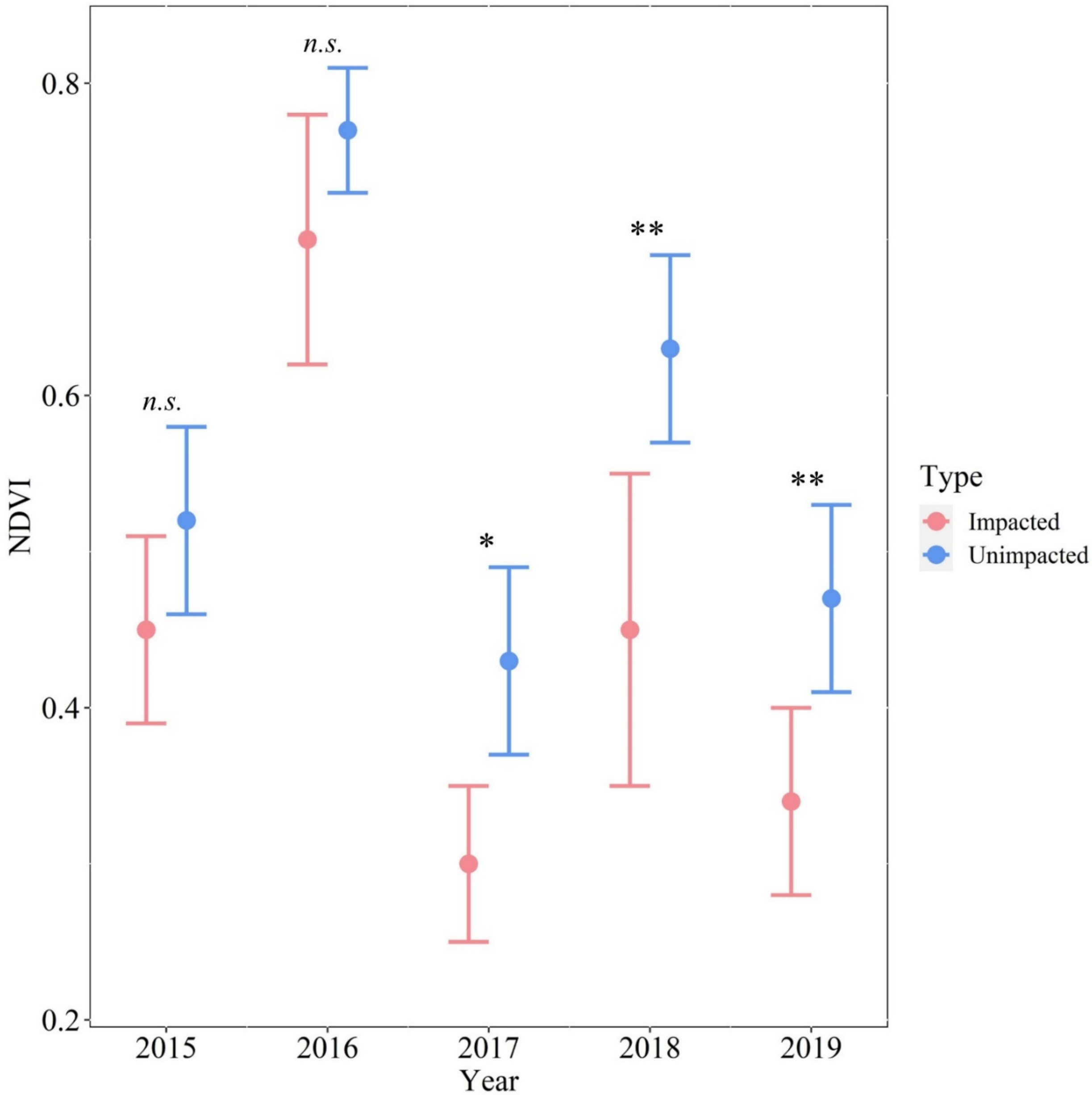



**FIGURE 2**: Comparison of annual NDVI values (mean ± 1 SD) across impacted and unimpacted wetlands at the Original Pocahontas Off-Road Vehicle Trail System in Tazewell County, Virginia. Labels denote significance levels of comparisons between impacted and unimpacted wetlands within each respective year (n.s. = non-significant; * = $P < 0.05$; ** = $P < 0.01$).

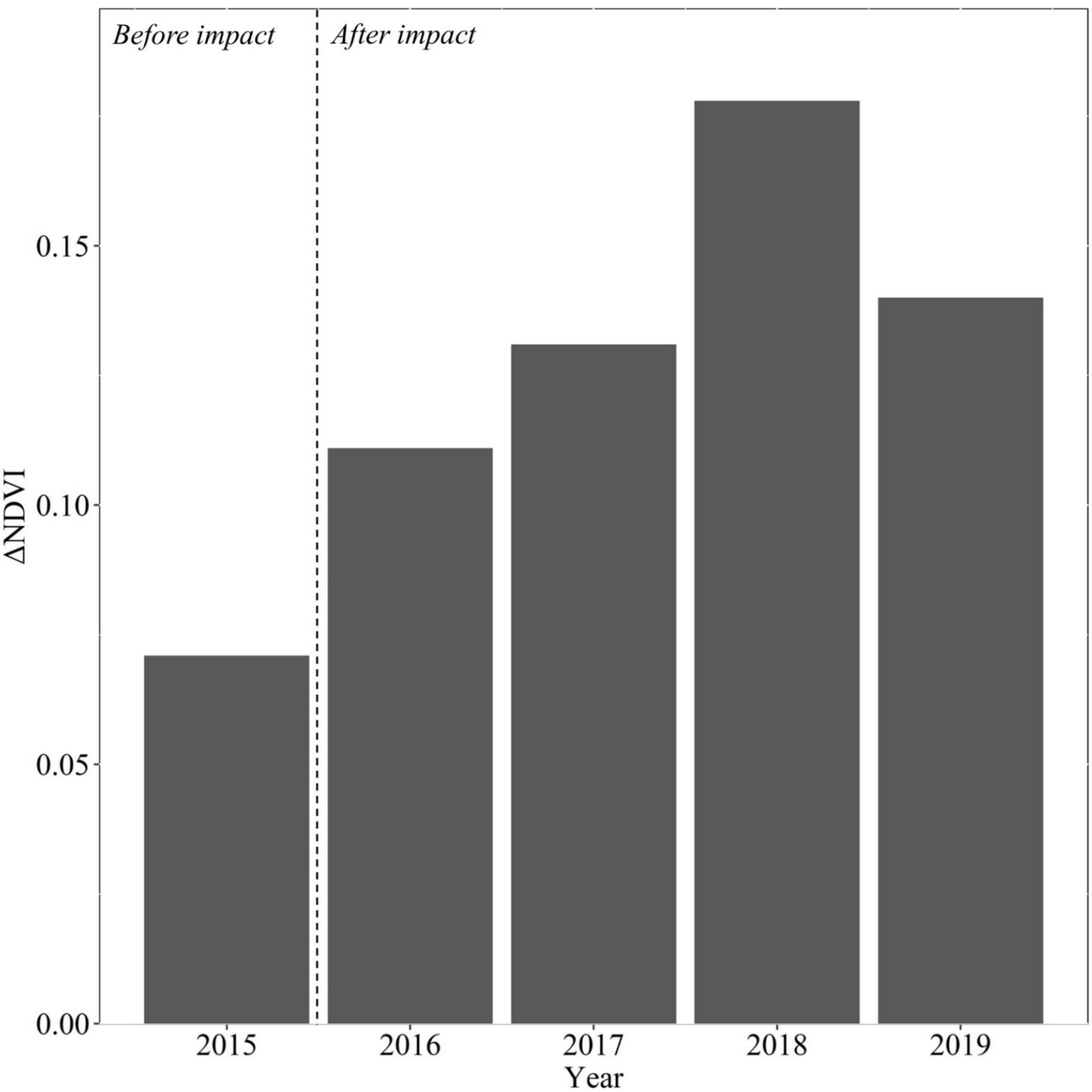
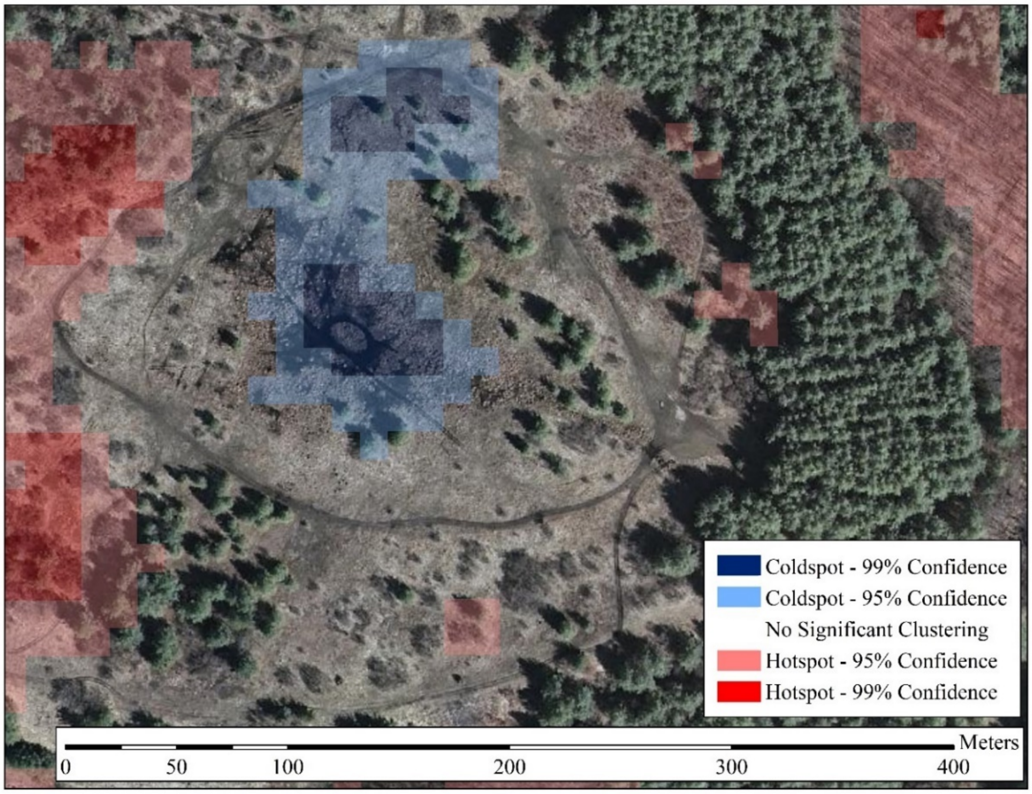



**FIGURE 3**: Differences in mean NDVI (ΔNDVI) between wetlands impacted by off-road vehicle disturbance and those unimpacted by off-road vehicle disturbance at Virginia's Original Pocahontas Trail System per year from 2015-2019. 2015 represents the year prior to the full study area's opening to motorized users; impacted wetlands were open to motorized vehicle use in each successive year.

(Fig. 4, A)


Coldspot - 99% Confidence
Coldspot - 95% Confidence
No Significant Clustering
Hotspot - 95% Confidence
Hotspot - 99% Confidence
Meters
0
50
100
200
300
400

(Fig. 4, B)

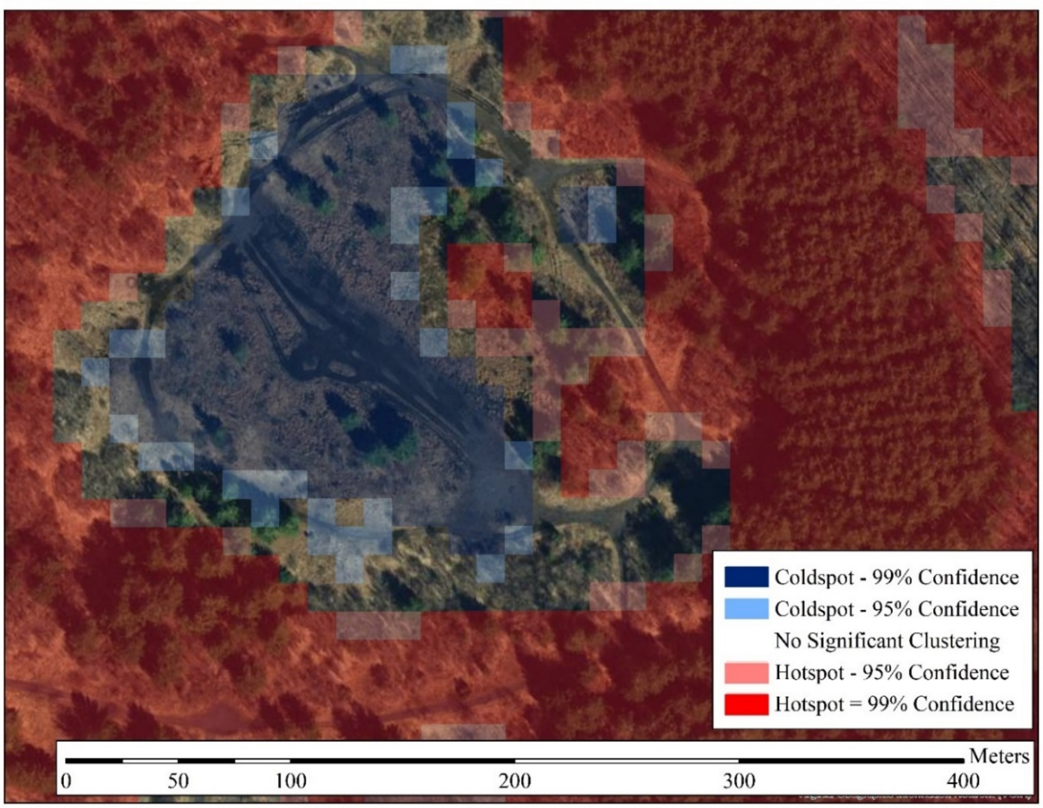

Coldspot - 99% Confidence
Coldspot - 95% Confidence
No Significant Clustering
Hotspot - 95% Confidence
Hotspot = 99% Confidence
Meters
0
50
100
200
300
400

**FIGURE 4:** Representative example of NDVI coldspot formation over time at a single wetland site impacted by off-road vehicle trails (Trail 10) in Tazewell County, Virginia: (A) wetland prior to the trail system's opening, and (B) the same wetland in 2019 after multiple years of being open to off-road vehicle use. Note substantial scouring of vegetation and underlying soils in tire tracks from vehicle travel accompanying separate NDVI coldspot in 2019.
(Fig. 4, B)

**TABLE 2**: Proportion of wetland areas at the Original Pocahontas Off-Road Vehicle Trail System comprised of statistically-significant NDVI coldspots per year. "Impacted" denotes wetlands co-located with official off-road vehicle routes and exhibiting signs of vehicle disturbance (tire rutting, vegetation scouring), while "unimpacted" denotes wetlands not co-located with official vehicle routes. 2015 denotes the year prior to the onset of wetland impacts, with impacted wetlands open to vehicle use in each successive year. Asterisk denotes one year's imagery that resulted in inflated NDVI values across the entire Sentinel-2 tile; see text for discussion of this outlier.

| Wetland | Type | 2015 | 2016* | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|---|
| Trail 10 | Impacted | 0.33 | 0.32 | 0.53 | 0.95 | 0.87 |
| Trail 80 | Impacted | 0.62 | 0 | 0.67 | 0.89 | 0.73 |
| Trail 90 | Impacted | 0.23 | 0 | 0.2 | 0.68 | 0.46 |
| Curran Branch | Unimpacted | 0.08 | 0 | 0 | 0 | 0.01 |
| Farmers Branch | Unimpacted | 0.1 | 0 | 0.09 | 0.24 | 0.11 |
| Haynes Branch | Unimpacted | 0.08 | 0 | 0 | 0.26 | 0.02 |

## DISCUSSION

Remotely-sensed indices of ecological condition are commonly used to assess spatiotemporal changes in the condition of wetlands and other habitat types (Pettorelli et al. 2005). In particular, NDVI and associated metrics have been found to serve as an indicator of wetland condition that can highlight signatures from a variety of wetland disturbances, including severe storm events (Rodgers et al. 2009), commercial development and agricultural practices (Kayastha et al. 2012; Alatorre et al. 2016), short-term spill events involving chemical pollutants (Jaramillo et al. 2018), and wildfires (Potter 2018). The results of this study suggest that these same indices are also capable of detecting patterns of anthropogenic disturbance in wetlands targeted for motorized vehicle trail development in mountainous terrain. One strength of this study was being able to statistically compare remotely-sensed indices across wetlands whose disturbance histories were known, clarifying signatures associated with wetland disturbance that may be beneficial for land managers and others seeking to gauge the extent of wetland disturbance in other areas.

In particular, a common index of vegetation health (NDVI) showed significant differences between impacted and unimpacted wetlands, with differences in NDVI values increasing across wetland types over time after the study area was opened to the public as a motorized recreation area. One interesting pattern apparent in this dataset was that NDVI values across all sites increased in 2016 relative to other years, regardless of disturbance history. This pattern was consistent across the entire Sentinel 2 tile used to render NDVI data, even at sites characterized by unvegetated and impervious surfaces. Why this particular pattern occurred for 2016 is unclear, although this may be due to artifacts from high cloud contamination or other atmospheric effects (Eklundh 1995; Ali et al. 2013). However, the general patterns of significance and model support for the NDVI comparisons reported above were unchanged when evaluating models with data from this year excluded as a potential outlier.

Lower NDVI values in wetlands impacted by off-road vehicle use would be expected, since past research has shown that such development can have detrimental impacts on wetland habitats. Both wetland vegetation and the soils necessary for the establishment of wetland plant assemblages, for example, can be negatively impacted by persistent off-road vehicle use (Hannaford and Resh 1999; Trip and Wiersma 2015), with soil damage potentially persisting for years following an initial disturbance event (Ahlstrand and Racine 1993). Vehicle scouring of the type observed across the study area during field visits should therefore be expected to remove emergent vegetation cover and replace it with open substrate, leading to a decrease in NDVI values relative to nearby unimpacted wetlands, whose vegetation assemblages have not been physically disturbed. Indeed, past work with both natural and anthropogenic wetland disturbance has found similar signatures of decreasing NDVI values during and following disturbance events (Potter 2018; Wilson and Norman 2018; Taddeo et al. 2019; Vanderhoof et al. 2020).

Most importantly, NDVI values not only decreased within impacted wetlands but showed increasing patterns of statistically-significant coldspot development over time, highlighting the clustering of low NDVI values. Such clustered values are valuable since they reflect spatially-coherent patterns of NDVI maxima or minima, rather than scattered noise reflecting extreme NDVI values in single pixels or grid cells (Boschetti et al. 2013; Chakraborty et al. 2018). The observed trend of coldspots increasing in size in impacted wetlands over time is consistent with increasing wetland disturbance from persistent off-road vehicle use, especially when coupled with a relative lack of statistically-significant coldspots in adjacent unimpacted wetland habitats. In fact, Getis-Ord analyses indicated that these unimpacted wetlands actually exhibited even some NDVI hotspot development in several cases, indicating an increase in vegetation health at the same time nearby impacted wetlands were experiencing growing clusters of NDVI minima.

These results suggest that NDVI data may be particularly useful for researchers and land managers charged with assessing the extent of wetland disturbance as a result of motorized vehicle use. In particular, the consistent or growing presence of statistically-significant clusters of NDVI minima within wetlands across a time series appears to be strongly indicative of vegetation loss associated with wetland disturbance. Since satellite data producing spectra required for the calculation of NDVI are freely and publicly available from a variety of sources, the approach outlined in this study may be especially useful in cases where other remotely-sensed data sources, such LiDAR coverage and high-resolution orthoimagery, are unavailable to assist in the landscape-scale detection of wetland change.

However, there are several important limitations to the approach outlined in this study. First, researchers should use caution when ascribing differences in NDVI values to specific forms of disturbance, such as the off-road vehicle use investigated in this study, when the disturbance histories of wetland sites are not known *a priori*. For example, temporal changes in NDVI are not solely caused by anthropogenic disturbances but may also reflect natural disturbance events, stressors such as drought or disease, and changes in vegetation assemblages resulting from ecological succession (Piao et al. 2006; Franke and Menz 2007; Zhao et al. 2009). The NDVI differences outlined in this study were strongly indicative of anthropogenic disturbance from motorized vehicles due to (i) the known disturbance histories of the wetlands selected for study, and (ii) the ability to statistically compare wetlands impacted by motorized vehicle use and those unimpacted by these and other disturbances across the same spatial extent and time period. However, other areas where this approach is applied may not have the luxury of pre-existing knowledge about the recent disturbance histories or condition of focal wetlands, meaning that trends in NDVI minima should not be viewed as a sole indicator of anthropogenic disturbance. Instead, these data are likely best suited as an initial step in screening wetlands for putative disturbance events, with follow-up comparisons via high-resolution aerial orthoimagery and/or field assessments necessary to fully gauge such impacts.

Second, this study was restricted to primarily open-canopy wetlands not located beneath thick forest cover. While most wetlands located in mid- or upslope positions in the study region possess such structural attributes, particularly for wetlands formed on former surface mines (Thompson et al. 2007; Atkinson et al. 2010), floodplain and riparian wetlands located along rivers and other large waterways may not share these characteristics and may be located in closed-canopy situations. These wetland types were not present in the immediate study area, and it remains unknown if and how the presence of a dense forest canopy may impact NDVI values in cases where disturbance activities impact wetland vegetation closer to the ground layer and do not result in the removal of overstory vegetation. NDVI data from all habitats may also be seasonally variable in response to senescence late in the growing season, dormant vegetation outside of the growing season, and increasing greenness during spring months (Zoffoli et al. 2008; Lumbierres et al. 2017; Xu et al. 2017), potentially confounding NDVI-based assessments of wetland condition if comparisons of a collection of sites are made using imagery from widely differing dates or seasons. Assessing these impacts may be one potential area for future study.

The detection of changes in NDVI data following disturbance events is also likely dependent on the resolution of the satellite datasets used to calculate NDVI and related indices. The Sentinel-2 data used here are among the most high-resolution (10 m) multispectral data publicly available. While these data appear to be able to effectively detect wetland change within the study region, more high-resolution datasets do exist from proprietary sources and may be able to more effectively detect wetland change due to various forms of anthropogenic disturbance. Similarly, more coarse-resolution data from publicly-available data sources such as the Moderate Resolution Imaging Spectroradiometer (MODIS; Ardanuy et al. 1991) and Advanced Very High Resolution Radiometer (AVHRR; Holben 1986) may be less capable of detecting change in wetlands of the size used in this study, making the source of remotely-sensed data a critical consideration for others seeking to adapt this study's approach.

In conclusion, NDVI data can be a useful tool for detecting signatures of disturbance from motorized vehicle use in open-canopy wetland habitats, particularly when coupled with statistical approaches designed to detect spatially-coherent patterns of NDVI gain or loss. The results of this study underscore the ability for NDVI data to detect small-scale disturbances in wetlands, adding to a growing list of disturbances from both natural and anthropogenic sources that are detectable in wetlands using NDVI data. The off-road vehicle use and associated habitat disturbances investigated in this study are growing in scope and intensity across the central Appalachians and are presently considered one of the predominant forms of landscape change and associated conservation threats for some aquatic taxa across this region (USFWS 2016). However, little to no information currently exists on the regional extent of such disturbances in wetland ecosystems. As research into the extent of such disturbances, their ecological impacts, and potential mitigation measures increases both within the central Appalachian region and beyond, these remote sensing approaches may form a key tool alongside traditional field-based habitat assessments.

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