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Retrospective Analysis of the Spectral Properties of a Bog Changed by Road Construction

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Abstract: Peatland ecosystems ecosystems in mineral extraction areas experience anthropogenic impacts because of the construction of seismic survey lines, power lines, temporary and permanent roads, as well as pipelines. Accurately assessing the impact of construction projects such as roads on ecosystems can provide scientific basis for ecosystem protection. The assessment of the impact of roads on moisture and vegetation properties could be based on information about these properties before and after construction. This study proposes an algorithm for delineating the road influence zone on a bog by analyzing retrospective changes in spectral properties before and after road construction. Using archival Landsat images (2000–2021), we quantified statistically significant changes in spectral indices (NDWI, NDMI, MNDWI, GVMI, EVI, and CVI) around a road built in 2007 on an oligotrophic bog in Western Siberia. It was found that over the time interval from 2007 to 2021, the MNDWI index significantly decreased by 125% on a specific area of 96,280 m^2 km^{-1}. Statistically significant increases in the spectral indices NDWI, NDMI, GVMI, EVI, and CVI were observed only sporadically (in space). The results presented will serve as the basis for calculating changes in the specific emissions of CO_2 and CH_4 in the studied area. In addition, the obtained data can be used for a preliminary assessment of the area and magnitude of possible changes in the properties of the wetlands before the construction of permanent and temporary roads and can also be scaled to a larger area.

Keywords: road construction, oligotrophic bog, wetland vegetation cover, moisture of the underlying surface, Western Siberia.

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1. Introduction

Peatland ecosystems are natural long-term sink of atmospheric CO_2, stored in the peat, and they are a source of CH_4. This makes them one of the key components of the carbon cycle of the land-atmosphere system [*IPCC Climate Change…*, 2013; *Joosten et al.*, 2016]. Throughout the Holocene, wetlands have accumulated 500 Gt of carbon in peat deposits, which is comparable to the phytomass of forests, assuming they occupy an order of magnitude smaller area [*Assessment on Peatlands...*, 2008; *Dise*, 2009; *Xu et al.*, 2018]. Given increasing anthropogenic pressures and climate change, preserving these carbon stocks and maintaining the sink function of peatlands is critically important [*IPCC Climate Change…*, 2013; *Joosten*, 2024].

Wetland ecosystems, especially those located in mining areas, experience anthropogenic impact from the development of seismic survey lines, power lines, temporary and permanent roads, and pipeline installations [*Pasher et al.*, 2013; *Saraswati et al.*, 2019]. These interventions have direct and indirect effects on the carbon absorption capacity of wetlands.

Roads are the most extensive infrastructure and one of the most significant in terms of their impact on the natural hydrological conditions and vegetation cover of peatlands [*Bocking et al.*, 2017; *Campbell et al.*, 2012; *Partington et al.*, 2016; *Plach et al.*, 2017; *Saraswati et al.*, 2023; *Strack et al.*, 2017]. The construction of roads can lead to localized flooding and/or drainage of wetland areas over a stretch of several tens or hundreds of meters [*Saraswati et al.*, 2019; *Strack et al.*, 2017]. Directly under the roadbed, peat is compacted, which disrupts its hydrological conductivity and slows down lateral soil water flow. Changes in hydrological regime, moisture of the underlying surface, and water table levels are particularly severe in areas where roads are constructed across water flow lines. Several years after road construction, the altered hydrological regime can lead to changes in wetland vegetation [*Saraswati et al.*, 2023; *Strack et al.*, 2017], which may collectively increase CH_4 emissions and/or reduce CO_2 assimilation.

To assess the impact of roads on the hydrology and vegetation properties of wetlands, it is necessary to have information about these properties before and after road construction. Remote sensing (RS) data provide a valuable tool for such analyses, enabling the evaluation of spectral characteristics of wetland surfaces over time. Moreover, the use of RS data allows for accounting for the spatio-temporal heterogeneity of the underlying surface properties, which is extremely high in peatland ecosystems.

The aim of our study was to localize the zone of road influence on the peatland by analyzing the retrospective dynamics of the spectral properties of the underlying surface in the period before and after road construction.

2. Methodology

The study area is located at a boreal patterned bog (60°50′41″N and 70°6′20″E), which is situated 58 km east-southeast from Khanty-Mansiysk, Khanty-Mansi Autonomous Okrug (KhMAO), Russia. The road to the study area at the boreal patterned bog was constructed in 2007: it is an earthen embankment up to 2 meters high without asphalt paving. The road is positioned across the natural bog water flows directed from southwest to northeast: thus, one part of the bog complex (upon visual inspection) was presumably flooded, while the other was drained.

The impact of road construction (for a section 3.0 km long) on soil moisture and the vegetation cover of the bog complex was assessed using a retrospective analysis of the spatiotemporal variability of the spectral indices NDWI, NDMI, MNDWI, GVMI, EVI, and CVI. Median cloud-free summer (June–September) composites were generated using Google Earth Engine with Landsat-7 (2000–2005), Landsat-5 (2007–2011), and Landsat-8 (2013–2021) imagery.

Then, in MATLAB (MathWorks, USA), using the “ranksum” function, a pixel-by-pixel Mann-Whitney test ($p = 0.05$; grouping variable: “before” or “after” road construction) was conducted on a time series from 2000 to 2021. The aim was to create a sample of only those pixels where statistically significant differences in spectral index values by grouping variable were observed. Thus, the spatial localization of the road impact zone on the bog was performed. Then, a quantitative assessment of the relative magnitude of spectral index changes for the localized impact zone was carried out. For this, the median values of the spectral indices for significantly differing pixels (by space, for each year) were calculated using the “median” function. Finally, the difference in the averaged (from 2000 to 2005 and from 2007 to 2021) medians of the spectral index values before and after road construction were calculated.

3. Results and discussion

The retrospective analysis of the spectral characteristics of the underlying surface showed that: 1) the majority (71–84%) of pixels showing statistically significant differences (Mann-Whitney test, $p < 0.05$) between pre- and post-construction periods were concentrated along a 250-meter zone along the road (71–84% of them are within a 125-meter zone) 2) the largest share among them (from 81% in the case of MNDWI to 100% in the case of CVI) consists of areas with a decrease of spectral indices (Figure 1, brown) and they are mainly located northeast of the road, that is, on the drained part of the bog 3) contrary to expectations, a statistically significant increase in the spectral indices was not detected southwest of the road in the supposedly "waterlogged" part of the bog and is generally sporadic within the 250-meter zone from the road (Figure 1, turquoise). The decrease in median values (when comparing periods before and after road construction) of NDWI, NDMI, MNDWI, and GVMI ranged from −14 to −125%, which indicates: 1) the reduction of water content in the vegetation 2) the formation of drier soil conditions 3) the development of water stress in plants 4) the deterioration of their condition or replacement by more drought-resistant species.

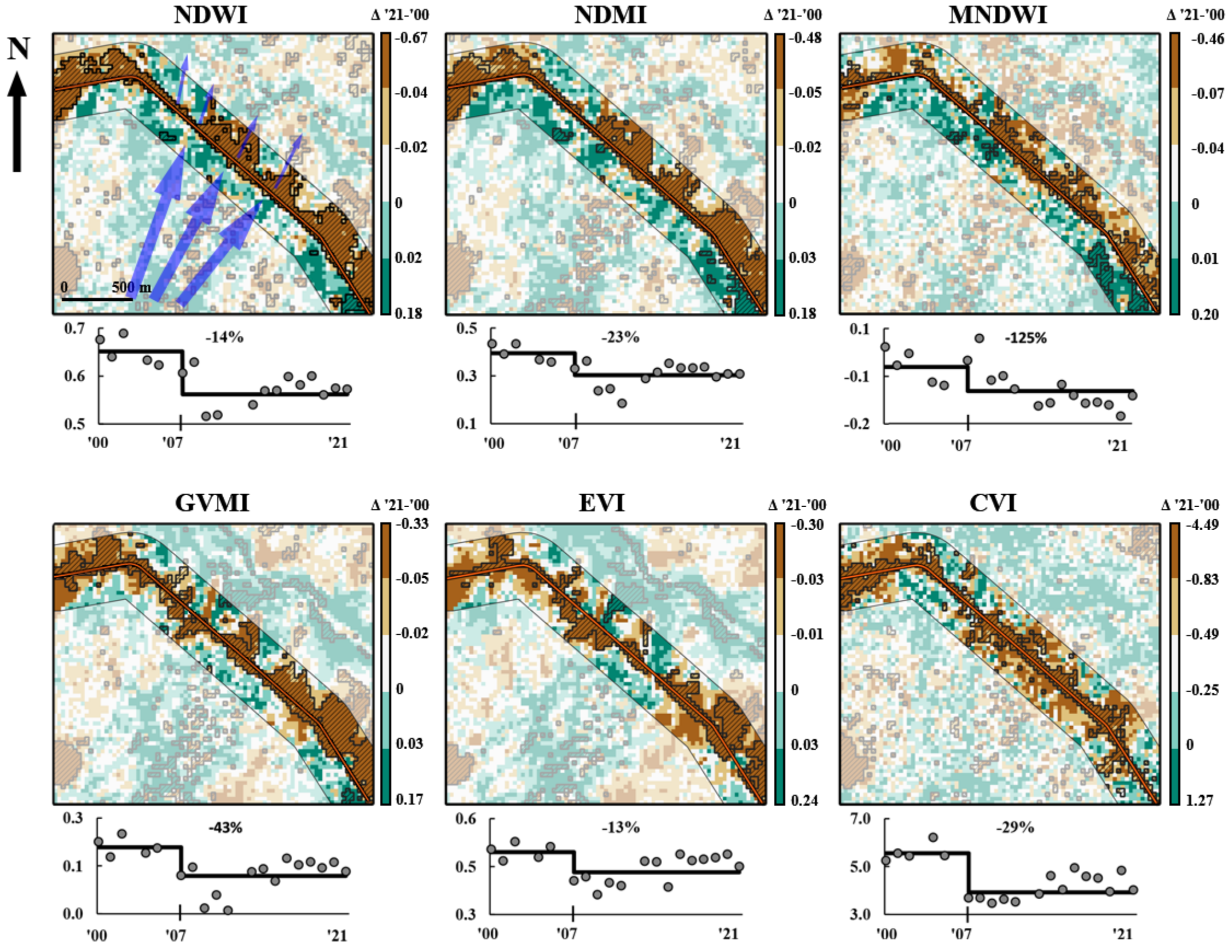

Figure 1. Schemes of the differences in median spectral index values in the bog area intersected by the road for the period before (2000–2005) and after (2007–2021) its construction. Pixels that significantly differed according to the Mann-Whitney test ($p \leq 0.05$, grouping variable: "before" or "after" road construction for the entire period under consideration) are shown with black outlines and hatching. Below the maps, the difference in median spectral index values (in groups before and after road construction) for pixels with $p \leq 0.05$ and their values by years are shown. Blue arrows indicate the direction of bog water flows.

The decrease in average EVI and CVI values was −13% and −29% respectively, which is usually associated with: 1) a reduction in the density of green vegetation 2) a decrease in chlorophyll content in leaves 3) a decline in productivity and photosynthetic activity of the vegetation cover. The decrease in EVI and CVI was more evenly distributed to the northeast and southwest of the road than NDWI, NDMI, MNDWI, and GVMI.

Conservatively evaluating the changes in the properties of the underlying surface of the bog because of road construction, we present the smallest impacted area: it was obtained using the MNDWI index and amounted to 288,839 m^2 (or 96,280 m^2 per km of road). In this zone, only the part that was subjected to statistically significant drying was considered.

Compared to earlier studies conducted on bog areas intersected by roads along bog water flow lines [*Saraswati et al.*, 2019; 2023; *Strack et al.*, 2017], we show a significantly larger (reaching up to 250 meters in some places) zone of road impact on bog moisture. The main consequence of road construction was the drainage of the bog portion downstream (to the northeast) from the road, whereas flooding upstream (to the southwest) was not detected. We hypothesize that the excess moisture in the bog area did not lead to terrain flooding due to drainage through one of two paths: 1) lateral drainage through roadside ditches leading outside our study area 2) engineered drainage via subsurface pipes directing water northeastward to adjacent river systems.

Undoubtedly, the vegetation indices are a relative indicator of changes in the properties of the underlying surface, and in our case, they are more qualitative (due to the lack of ground data on phytomass, surface moisture, and plant properties in previous years). However, they allowed us to localize the area of road impact on the vegetation and soil cover, as well as confirm the presence of long-term changes related not to random factors but specifically to road construction.

4. Conclusion

By implementing an algorithm to analyze retrospective spectral dynamics before and after road construction, we successfully localized the zone of hydrological and ecological impact on the studied bog. Key findings include that during the time interval from 2007 to 2021 (directly after the road was built), the MNDWI index value significantly decreased over a specific area of 96,280 $m^2\ km^{-1}$ by 125%. Also, statistically significant growth in the spectral indices NDWI, NDMI, GVMI, EVI, and CVI was observed only sporadically. The results presented will serve as a basis for calculating changes in the specific emissions of CO_2 and CH_4 in the area studied. Additionally, the obtained data can be used for a preliminary assessment of the area and magnitude of possible changes in the properties of the underlying surface of bogs before the construction of permanent and temporary roads and can also be scaled to a larger territory.

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