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# Complementary insights into high Arctic greening from absolute and relative NDVI trends across the Canadian Arctic Archipelago

# Perspectives complémentaires sur le verdissement du Haut-Arctique à partir des tendances absolues et relatives de l'indice NDVI dans l'archipel arctique canadien

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**ABSTRACT**

The interpretation of increasing vegetation, also called greening, using the normalized difference vegetation index (NDVI) remains challenging in sparsely vegetated regions. Vegetation changes in higher latitude regions have mostly been assessed through circumpolar studies, which place its magnitude in the context of more productive, lower-latitude ecosystems. However, absolute greening trends ($\Delta NDVI_{max}$) may underrepresent ecologically meaningful variation where plant cover is low. Here, we used four decades (1984–2023) of Landsat-based $NDVI_{max}$ time series to assess vegetation change across the Canadian Arctic Archipelago combining the commonly used Absolute Greening Index (AGI) and the Relative Greening Index (RGI; percent change relative to initial $NDVI_{max}$ based on 1984 data). Both metrics indicated widespread but low-magnitude greening, with stronger increases at higher latitudes. However, RGI revealed clearer differences among bioclimatic zones and emphasized vegetation change in sparsely vegetated northern regions, while AGI suggested more homogeneous trends. Specific examples showed that RGI highlighted subtle NDVI increases along coastal and patchy vegetation areas, whereas AGI provided a more conservative depiction of change. Our results suggest that using both metrics provide complementary insights into vegetation dynamics, improving interpretation of greening patterns across the Canadian Arctic Archipelago.

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**RÉSUMÉ**

L'interprétation de l'augmentation de la végétation, également appelée verdissement, à l'aide de l'indice de végétation par différence normalisée (NDVI : Normalized Difference Vegetation Index) est complexe dans les régions à végétation clairsemée. Les changements de végétation aux hautes latitudes ont principalement été évalués par des études circumpolaires, qui situent leur ampleur dans un contexte qui inclut des écosystèmes plus productifs situés à de basses latitudes. Cependant, les tendances absolues de verdissement (ΔNDVImax) peuvent sous-estimer les variations écologiquement significatives lorsque le taux de couverture végétale est faible. Dans cette étude, nous avons utilisé quatre décennies (1984-2023) de séries temporelles NDVImax issues de Landsat pour évaluer les changements de végétation dans l'archipel arctique canadien, en combinant l'indice de verdissement absolu (AGI : Absolute Greening Index), couramment utilisé, et l'indice de verdissement relatif (RGI : variation en pourcentage par rapport au NDVImax initial basé sur les données de 1984). Les deux indicateurs ont révélé un verdissement généralisé, mais de faible ampleur, avec des augmentations plus marquées aux hautes latitudes. Toutefois, le RGI a mis en évidence des différences plus nettes entre les zones bioclimatiques et a fait ressortir les changements de végétation dans les régions nordiques à végétation clairsemée, tandis que l'analyse par l'AGI montre des tendances plus homogènes. Des exemples précis ont montré que l'indice RGI mettait en évidence de subtiles augmentations de l'indice NDVI le long des zones côtières et des zones de végétation clairsemée, tandis que l'indice

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AGI offrait une représentation moins marquée des changements. Nos résultats suggèrent que l'utilisation conjointe de ces deux indicateurs apporte des éclairages complémentaires sur la dynamique de la végétation, améliorant ainsi l'interprétation des schémas de verdissement dans l'archipel arctique canadien.

## Introduction

The Arctic has warmed nearly four times faster than the global average over recent decades, resulting in substantial changes to terrestrial ecosystems (Rantanen et al. 2022). Earlier snowmelt, longer growing seasons, and shifting soil moisture regimes are altering plant growth and vegetation composition across high-latitude landscapes (Brown et al. 2010; Prevéy et al. 2019; Mudryk et al. 2020; Myers-Smith et al. 2020; Levasseur et al. 2021). Increases in vegetation productivity over time reported from satellite imagery are commonly described as Arctic 'greening' (Berner et al. 2020; Bayle et al. 2022).

Greening at the higher latitudes has mostly been assessed through circumpolar studies, using spectral indices such NDVI (Normalized Difference Vegetation Index, Walker et al. 2005, Berner et al. 2020). At this large scale, the contrast between more productive and lower-latitude ecosystems gets emphasized when compared to higher latitude regions with scarce vegetation. For example, Ju and Masek (2016) found relatively small trends in the Canadian Arctic (0–0.004 NDVI/year), compared to stronger greening near the taiga-boreal forest boundary (~0.008 NDVI/year). Similarly, Berner et al. (2020) found an absolute greening of 0.007 NDVI/year in the higher latitudes of the Arctic, versus 0.036 NDVI/year across the entire Arctic biome. These small NDVI increases suggest limited greening when compared geographically, yet in situ observations have reported changes in plant cover and community composition in the High Arctic (O'Kane and Henry 2024, Berner et al. 2024).

The NDVI is widely used as a proxy for vegetation productivity because chlorophyll absorbs visible wavelengths while leaf structure reflects near-infrared radiation (Rouse 1973). NDVI is a nonphysical unidimensional indicator sensitive to vegetation canopy properties such as biomass and photosynthetic activity (Tucker 1979). Long-term vegetation changes are often evaluated using changes in annual maximum NDVI ($NDVI_{max}$), representing peak photosynthetic activity during the growing season (Myers-Smith et al. 2020). However, interpreting NDVI trends across Arctic ecosystems remains challenging due to varying vegetation horizontal and vertical cover (Davidson et al. 2016; Edwards and Treitz 2017), non-linear relationships between NDVI and biophysical parameters along its spectrum (Myers-Smith et al. 2020), and diverse ground features (e.g., soil, rock, topography) with unique moisture and reflectance properties that influence NDVI values (Bayle et al. 2021). The ecological and technical limitations of using the NDVI signal, although correlated with photosynthesis, are well-known and limit the interpretation of the ecological changes in the ecosystems studied (Myers-Smith et al. 2020). Nevertheless, greening remains difficult to assess for the Canadian Arctic Archipelago, which represents a large north-south gradient (Edwards and Treitz 2017). Thus, the interpretation of change over a wide gradient explores the rate of change in low-productivity regions by contrasting them with more productive ecosystems in the south. A better comprehension of the impacts of greening is required to assess the implications of vegetation change on the assembly of northern ecosystems.

To better interpret vegetation changes across sparse and dense vegetation ecosystems, NDVI-based approaches that incorporate both the rate of greening and its magnitude relative to the initial state may be needed. Absolute NDVI trends provide robust gradients of change at broad spatial scales, whereas relative changes may better depict subtle greening where initial vegetation cover is low. The objective of this study is to characterize spatiotemporal vegetation change in the Canadian Arctic Archipelago from 1984 to 2023 by comparing two NDVI-derived metrics:

1. the Absolute Greening Index (AGI)—rate of change in $NDVI_{max}$, and
2. the Relative Greening Index (RGI)—proportional change in $NDVI_{max}$ relative tobaseline conditions (i.e., $NDVI_{max}$ 1984).

We hypothesize that these two metrics offer complementary perspectives: AGI will more effectively capture greening trends in more productive ecosystems, while RGI will capture ecologically significant yet low-magnitude changes in sparsely vegetated high-latitude zones. By combining relative and absolute greening metrics, we aim to improve assessments of vegetation change across the strong latitudinal and environmental gradients of the Canadian Arctic Archipelago.

## Data and methods

### Study area

Our study area encompasses most of the Canadian Arctic Archipelago spanning a gradient of five bioclimatic zones, as defined by the Circumpolar Arctic Vegetation Map (CAVM, Figure 1). For this study, we rely on the CAVM bioclimatic zone characterization to distinguish areas where greening is likely to differ. These zones correspond to different thresholds of variables, such as the mean July temperature and dominant plant functional types (Walker et al. 2005). The three northernmost vegetation zones, namely the Polar Desert, Northern Arctic tundra, and Mid-Arctic tundra, are in the higher latitudes, whereas the Southern Arctic tundra and Arctic shrub-tundra are in the lower latitudes (Figure 1; Walker et al. 2005). According to Elvebakk et al. (1999), the Polar Desert zone has the coldest temperatures in summer, and vegetation is dominated by herb and graminoid plant communities mixed with barrens (unvegetated rocky areas). The Northern Arctic tundra zone is the second coldest area with sparse vegetation and is characterized by a mixture of forbs, prostrate shrubs, mosses, and lichens. According to the CAVM classification, plant diversity increases in the Mid-Arctic tundra zone, where there are dwarf shrubs (<15 cm in height), prostrate shrubs, graminoids, and cryptogam communities with denser vegetation cover. The Southern Arctic tundra zone is dominated by closed vegetation cover, which includes erect shrubs (>15 cm) and abundant wetlands and marshes. Finally, the southernmost and warmest zone is the Arctic shrub-tundra. It is located at the northern tip of the western continental area and is dominated by erect shrubs and mires.

### NDVI time series

To create a time series of annual $NDVI_{max}$ maps, we used the Tier 1 data available for our study site from 1984 to 2023 in Landsat Collection 2, as provided by the United States Geological Survey (USGS) and hosted on Google Earth Engine (GEE; Gorelick et al. 2017). We are aware that the number of images from the Landsat collection changes over time and according to latitude which may affect the greening signal

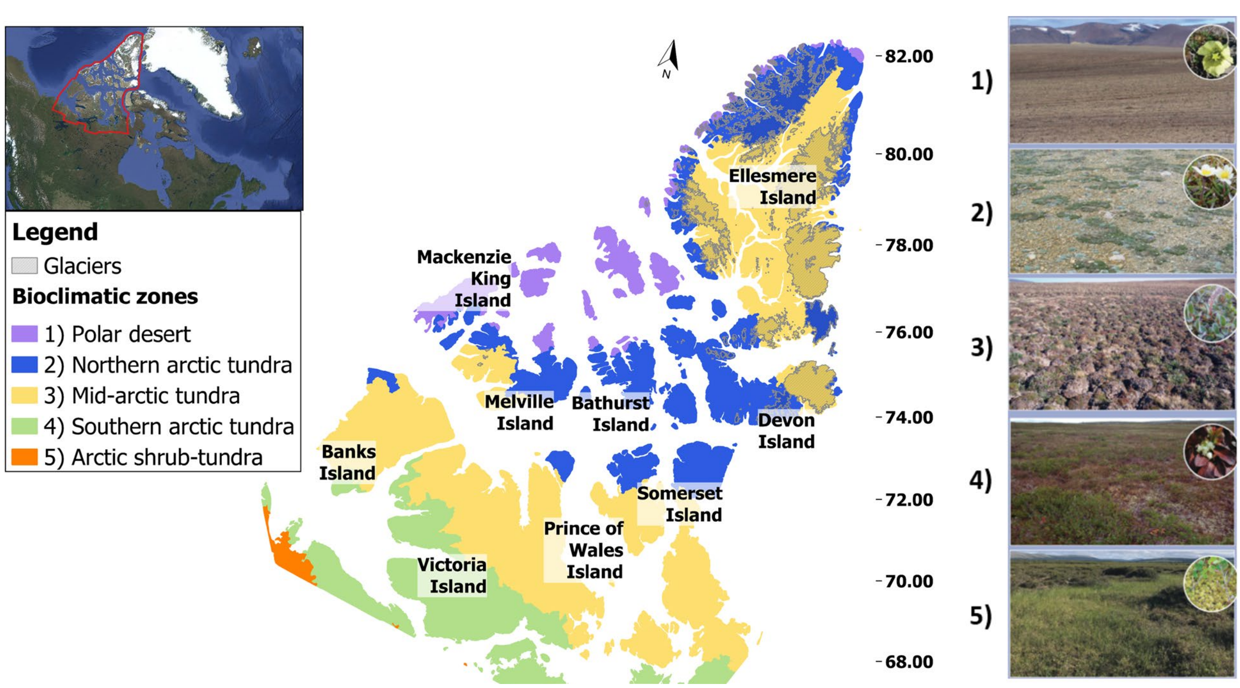


Figure 1. Location of the study area in the Canadian Arctic Archipelago, with the five bioclimatic zones as defined by the Circumpolar Arctic Vegetation Map (CAVM). Photos are from the Raster CAVM Vegetation description (CAVM Team, 2024).

(Bayle et al. 2024), but applying available correction pixel-wise over the whole Canadian Archipelago is too computationally intensive. Moreover, potential biases would affect both absolute and relative indices, which would not alter the main results of the study. The Tier 1 data products included surface reflectance from the Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper + (ETM +), and Landsat 8 Operational Land Imager (OLI) at 30 m × 30 m resolution per pixel. We performed cross-sensor calibrations to correct for systematic radiometric discrepancies in the NDVI among sensors using the methods and coefficients of Berner et al. (2023). Similar to Goetz et al. (2005), the images were filtered annually for periods between mid-July and mid-August (dayof the year 196–227) to capture the peak of the Arctic growing season. A mask for cloudy pixels, shadows, snow and water was applied by applying a bitmask on the quality assessment band for the Landsat data in GEE. Nevertheless, visual inspection showed that GEE's first internal mask left some water and glaciers pixels. Post-treatment of the image collection extracted from GEE was performed to remove glaciers, water, and permanently snow-covered areas, as defined by the CanVec series data (Natural Resources Canada 2017). For each year, $NDVI_{max}$ was calculated for each pixel to create a time series of the annual $NDVI_{max}$ over 39 years across the entire archipelago. Moreover, Bayle et al. (2024) showed that, because Landsat observations increase over the time series, the dependence of NDVImax on sampling frequency can lead to an overestimation of greening. A method to correct for this bias is available in the 'LandsatTS' R package (Berner et al. 2023). We did not used this correction as the R package is limited to 100,000 samples and our analysis rely on more than 3 billion of pixels, making it impossible to apply it. However, the proposed approach handles this uncertainty by making similar corrections in GEE. In addition, almost all the study area has more than 3 images available each year, which is the threshold for this overestimation of greening (i.e., Bayle et al. 2024).

### *Vegetation greening indices*

We explored two indices related to the NDVI, an absolute index and a relative index expressed as a percentage to depict greening in the Canadian Arctic Archipelago. The first metric was the AGI, which is used as a proxy for vegetation change (e.g., Myneni et al. 1997). AGI was calculated using the Theil-Sen slope estimator to measure the rate of change between each growing season from 1984 to 2023 in GEE (Equation (1)). This estimator has been widely used because it is less influenced by outliers than estimators that use linear regression (Forkel et al. 2013). This produced a map of the rate of change of the AGI from 1984 to 2023 for each pixel in the study area.

$$Absolute\ Greening\ Index = \sum \tilde{X}\left(\frac{(NDVI_{\max T+1} - NDVI_{\max T})}{(T_{+1} - T)}\right) \tag{1}$$

Our second index was the RGI. This index was calculated by multiplying the absolute greening in $NDVI_{max}$ over the time series (AGI) by the number of years in the temporal series and dividing by a reference value from the beginning of the time series (here 1984, which corresponds to the beginning of Landsat imagery available), as shown in Equation (2). Thus, the RGI represented an increase in the AGI relative to the initial 1984 $NDVI_{max}$ value. To reduce the stochasticity of the reference values in the RGI calculation, we simulated the 1984 $NDVI_{max}$ data using Sens' Intercept estimator in GEE, which is based on trends from the time series. To ensure that pixels were minimally impacted by possible water and snow cover, we constrained the dataset from the 1984 $NDVI_{max}$ by excluding pixels smaller than or equal to 0.1 from further analyses. The choice of a threshold of 0.1 NDVI is based on different studies that show that Landsat pixels with more or less than 15% of fractional vegetation cover will result in a NDVI of 0.1, a value usually considered as the threshold for vegetation (Bayle et al. 2021, Fretwell et al. 2011). By restricting $NDVI_{max1984}$ to 0.1, this ensures we avoided working with mixed water, snow, ground pixels, allowing for proper ecological interpretation of the index. Thus, the RGI theoretically ranges between −11 to 9 because $\Delta NDVI \in [-1,0.9]$ and $NDVI_{max1984} \in [0.1,1]$ so $RGI \in [-11,9]$. However, the observed distribution is more restricted than theoretical values (see Figure 2D), which corresponds to an ecological interpretation with a low

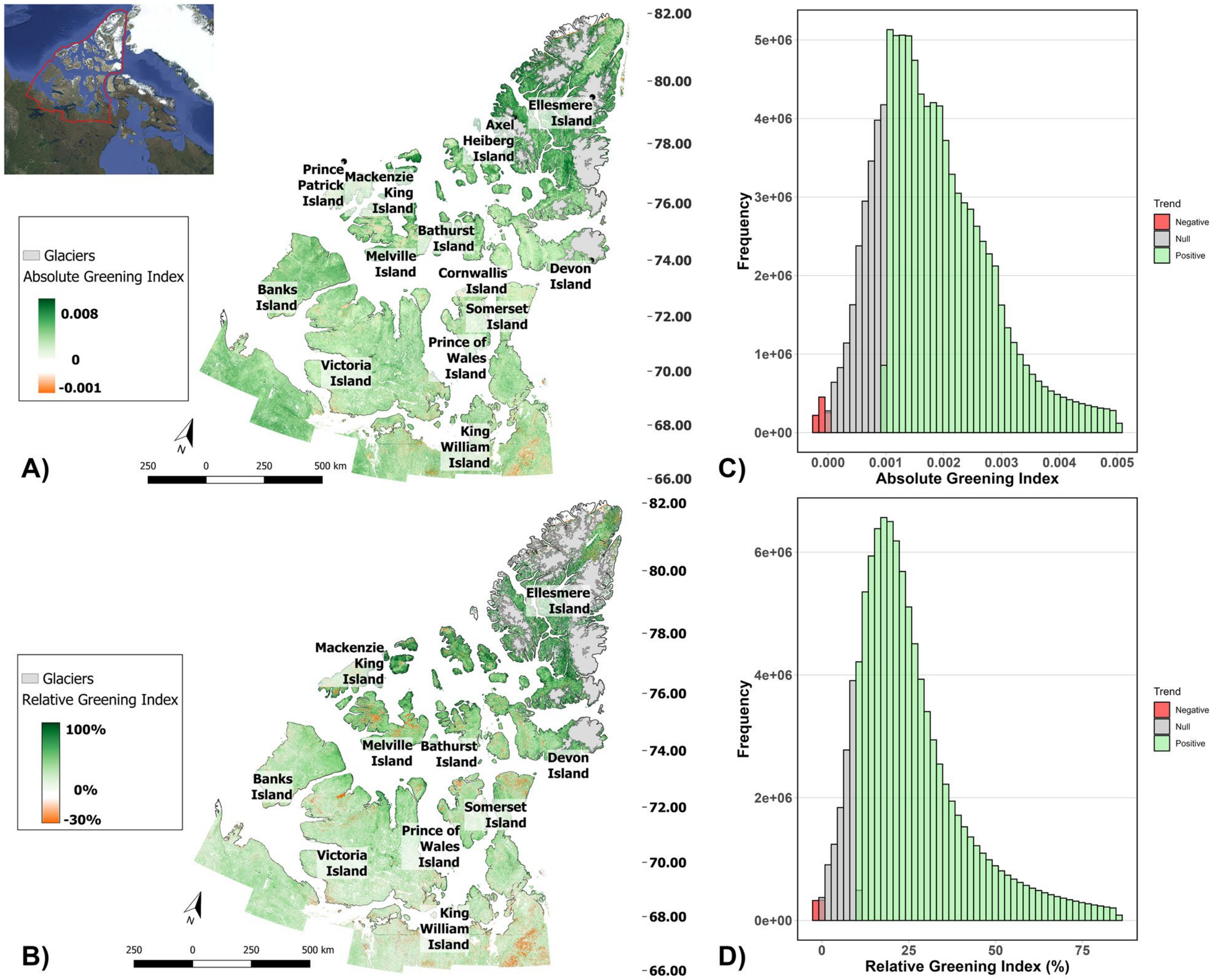


**Figure 2.** $NDVI_{max}$ rate of vegetation change in the Canadian Arctic Archipelago between 1984 et 2023 based on the temporal series of Landsat imagery. (A) Absolute Greening Index (AGI) and (B) Relative Greening Index (RGI) in percentage. (C) Distribution of the $NDVI_{max}$ values for AGI. positive trend (> 0.001) is green, null trend (between −0.001 and 0.) is grey and negative trend (<-0.001) is red. (D) Distribution of the $NDVI_{max}$ values for RGI. Positive trend (>10%) is green, null trend (between 0% and 10%) is grey and negative trend (<0%) is red. The distribution's 95% interval is displayed allowing to focus on the ecologically significant ranges for each histogram.

trend toward vegetation change. The value of $NDVI_{max1984}$, which acts as a constant in the RGI calculation, is hence the primary difference between AGI and RGI. $NDVI_{max1984}$ impacts RGI especially for low values leading to an increased detection of small changes. For example, for a AGI = 0.001, if the initial $NDVI_{max1984}$=0.1 (low value), the RGI = 0.39, showing an important relative increase. However, for the same AGI, if the initial $NDVI_{max1984}$=0,5 (high value), the RGI = 0.078, showing a lower relative change because the initial vegetation presence was high at the site. This example shows how the RGI is exacerbed for low $NDVI_{max1984}$ values which translate in a stronger change detected when there is low vegetation at the beginning of the time series. For this index, we obtained a single layer of percentage change for each pixel in the study area. This relative index may be quite similar to AGI, but we suggest that comparing absolute greening to an initial value will better highlight subtle vegetation changes that are significant at higher latitudes. There are limitations, however, to RGI in regions that were free of vegetation in 1984 and have undergone significant change since then. Pixels with less than 0.1 NDVI were then removed from RGI calculation, these zones were not assessed in the calculation of the index to ensure that the two indices were compared throughout the same surface area. For instance, glacier retreating zones that have been colonized in the interval were not include in the calculation of the RGI.

$$Relative\,Greening\;Index = \left( \frac{(AGI) * 39}{NDVI_{max1984}} \right) * 100 \tag{2}$$

### Statistical analysis

First, we depicted greening values for the study area with AGI time series. We compared the AGI and RGI across CAVM bioclimatic zones. Bioclimatic zones data were downloaded from the Alaska Geobotany Center (2004) and resampled to the corresponding pixels for each index. The CAVM bioclimatic zones were used to delineate 5 biogeographical boundaries over the study area, which the $NDVI_{max}$ metrics correspond. We compared AGI and RGI responses to bioclimatic zones with a General Least Squares model and results show significant differences between AGI and RGI ($p < 0{,}05$) leading to further analyses. To assess greening at the pixel scale, we used analysis of variance (ANOVA; R core Team 2023) to compare the relationships among the bioclimatic zones for each index. When significant, a Tukey honestly significant difference (HSD) test was used to investigate differences among the groups (R studio). Owing to the large number of pixels analyzed ($n \approx 3{,}2 \times 10^9$), Tukey comparisons were all statistically significant. Therefore, we interpreted the overall trends that allowed one metric to be distinguished from another.

## Results

### Vegetation changes using greening indices

Analyses of both AGI and RGI between 1984 and 2023 show a general but low increase in $NDVI_{max}$ across the Canadian Arctic Archipelago (Figure 2). However, islands in the northern part of the Canadian Arctic Archipelago have experienced a larger change than locations at lower latitudes (Figure 2A,B) and these changes are more pronounced with RGI (Figure 2B) than with AGI (Figure 2A). The range of values for AGI and RGI are shown in the histograms corresponding to each index (Figure 2C,D). The distributions' 95% intervals are also displayed. Both histograms indicate a high number of pixels tending toward positive values (Figure 2C,D), suggesting a positive change in vegetation therefore a greening in the Canadian Arctic Archipelago. RGI excludes pixels with zero baseline values from histograms due to division by zero, but values close to zero are considered as null changes (Figure 2D). RGI boosts both positive and negative values compared to AGI since they are tied to 1984s $NDVI_{max}$ values, which were already low. A stronger greening of coastal areas is observed with RGI on various islands, especially at high latitudes, but this pattern is more subtle with AGI.

The vegetation change depicted by our analysis also reveals regions where the $NDVI_{max}$ decreases (also called browning; Figure 2). These regions represent approximately 6% of the study area. RGI (Figure 2B) highlights the areas with a stronger decrease in the $NDVI_{max}$ signal (Figure 2C,D). Examples of browning zones where the $NDVI_{max}$ decreased are (i) the Boothia Peninsula (south of Somerset Island), (ii) an area to the northwest of Victoria Island, (iii) parts of Melville Island and Prince Patrick Island, and (iv) a continental area east of King William Island. The AGI revealed a modest rate of change in these locations (Figure 2C), whereas the RGI shows a higher relative change averaging −20% over 39 years (Figure 2D).

Beyond archipelago-scale patterns, the generated time series enables a closer assessment of changes at a smaller scale, like a specific island in the archipelago. With a resolution of 30 m x 30 m, it is possible to capture vegetation changes to the island level, such as MacKenzie King Island (Figure 3). In this example, both indices show general greening, but the RGI highlights the contrast between vegetation change whether the $NDVI_{max}$ index is increasing or decreasing. On MacKenzie King Island, the RGI shows a more intense greening along the coast, whereas the greening inside the island is less pronounced (Figure 3B). Similarly, browning areas are highlighted with the RGI and suggests these zones are located near river deltas (Figure 3). On the other hand, variations in the $NDVI_{max}$ signal shows similar patterns in accordance with the island's geological deposits suggesting an underlying delimitation (Figure 3).

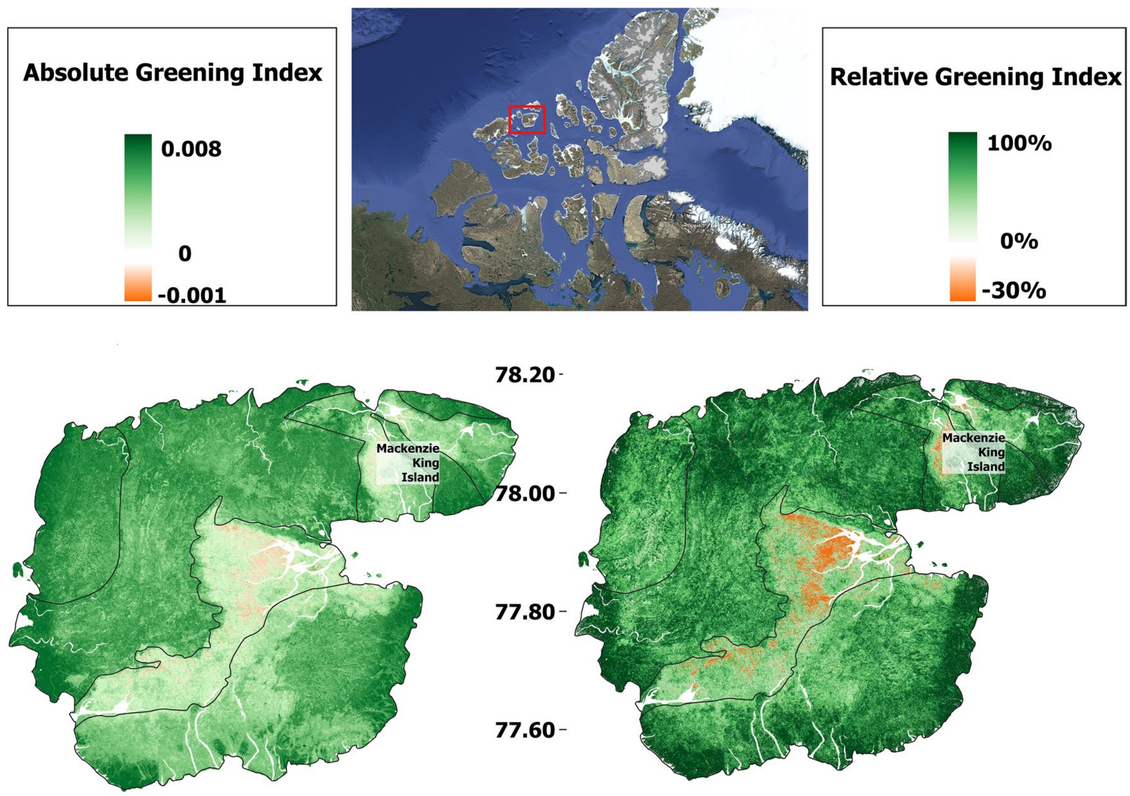


**Figure 3.** Zoom in on MacKenzie King Island for both indices. (A) The Absolute Greening Index (AGI). (B) The Relative Greening Index (RGI). Lines show geological boundaries according to Arctic Geobotanical Atlas (Alaska Geobotany Center, 2004).

### *Differences between bioclimatic zones*

The CAA shows distinct patterns of greening based on the different bioclimatic zones (Figure 4) and the latitudinal gradient (Figure 5). To assess the differences among the bioclimatic zones, we summarize the rate of change for each index in the five bioclimatic zones of the study region. The AGI shows stochastic differences among the different bioclimatic zones, which translates into no clear greening pattern across biomes (Figure 4A). For example, the mean change in the Northern Arctic Tundra zone is visually similar but statistically different ($P > 0.05$) from change in the Arctic Shrub-Tundra zone, and both experienced higher rates of change than the Southern Arctic Tundra. The variability is also similar for all bioclimatic zones for the AGI. In contrast, the RGI suggests a gradient between the bioclimatic zones with greater change as latitude increases and less greening at lower latitudes (Figure 4B). Visually, the RGI suggests two categories of change: one for the bioclimatic zones at higher latitudes, with greater variability for the Polar Desert, Northern Arctic tundra and Mid-Arctic tundra zones and one for lower-latitude zones, with small variability for the Arctic shrub-tundra and Southern Arctic tundra (Figure 4B). Nevertheless, both indices show the greatest variability in the Polar Desert zone. This difference between the two indices confirms that AGI and RGI provide different and complementary information across large areas such as bioclimatic zones.

A comparison of greening throughout different latitudes across the archipelago reveals the differences between the two indices (Figure 5). Lower latitudes (<73.4°) show a minor change in $NDVI_{max}$ according to both indices while higher latitudes (between 74.4° and 82.4°) show a distinct pattern of greening. With AGI, lower latitudes are under 0,002 NDVI (Figure 5A), which is sometimes considered as no trend in the literature, and only higher latitudes are described with greater values (between 0.002 and 0.004 NDVI). The vegetation changes recorded by our two indices indicates stronger greening above 77.4°N, with greater variability compared to lower latitudes. This greening can likely be attributed to the diversity of islands with different landscapes found at latitudes between

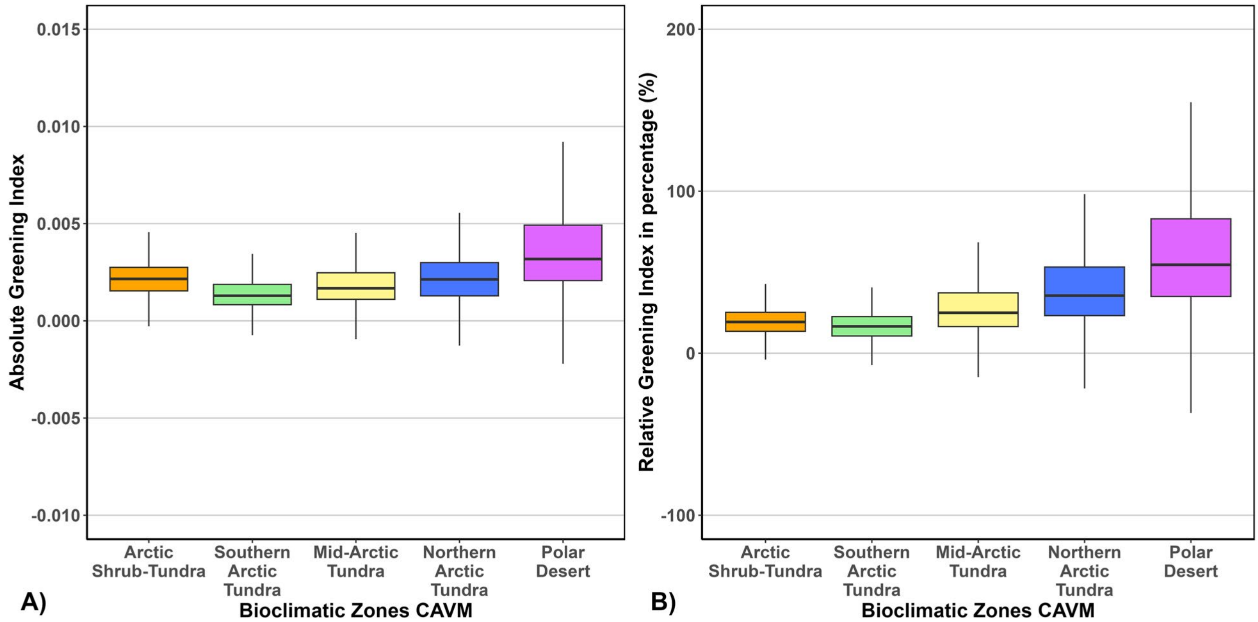


**Figure 4.** Greening trend for both (A) the Absolute Greening Index (AGI) and (B) the Relative Greening Index (RGI) for five of the bioclimatic zones (according to CAVM, Walker et al. 2005) over the Canadian Arctic Archipelago. Bioclimatic zones are presented from South to North, and NDVI values were calculated from Landsat imagery at 30 m × 30 m resolution.

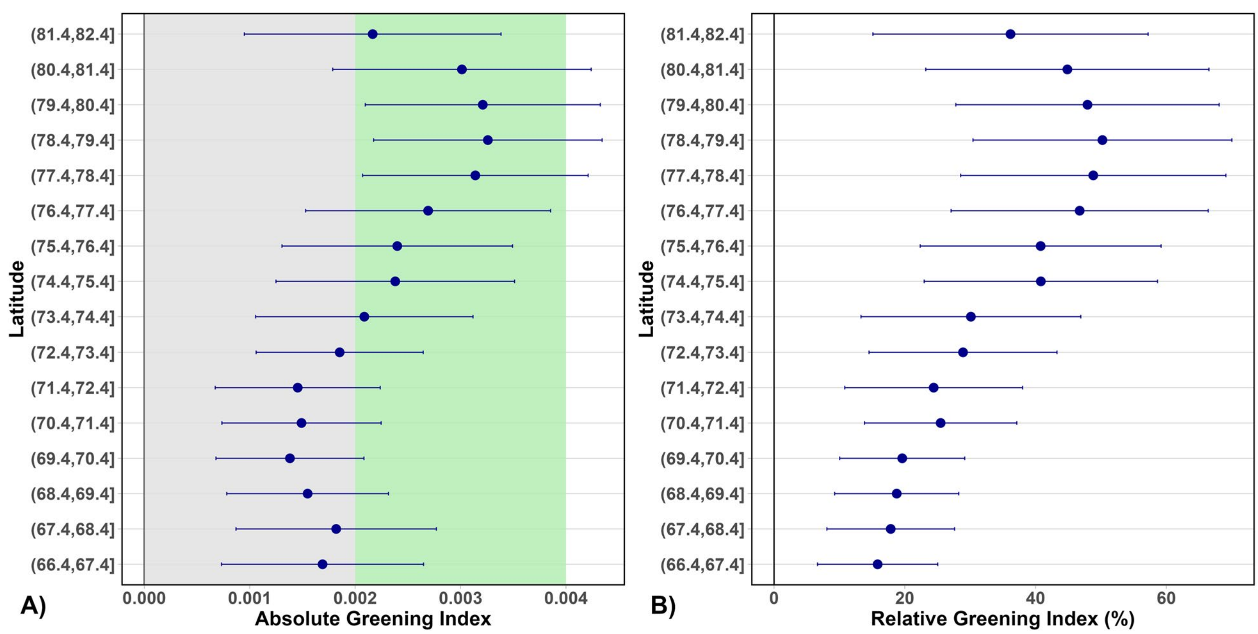


**Figure 5.** Greening trends per degree of latitude in the Canadian Arctic Archipelago for (A) the Absolute Greening Index (AGI), the grey band is the interval between 0 and 0.002 and the green band indicates 0.002 to 0.004 NDVI reported as minor trends by Ju and Masek (2016); (B) the Relative Greening Index.

77.4°N and 80°N. However, beyond 80°N, there is essentially just one island, Ellesmere Island, and the $NDVI_{max}$ trend depicts the variability within this island (Figure 5).

## Discussion

The products we developed highlight the complementarity of absolute and relative NDVI-derived indices for characterizing vegetation change in the Canadian Arctic Archipelago. Both approaches consistently indicate a widespread greening tendency over the study period, with the most pronounced trends occurring at higher latitudes. Although AGI and RGI depict an increase of vegetation over the study area (Figure 5), the amplitude and complexity of this change differ between the indices. The RGI amplifies positive and negative trends, resulting in a more distinct gradient of greening toward the high latitudes (Figure 2). In contrast, AGI shows smaller variability in the southern portion of the Archipelago, while RGI presents a more consistent transition across latitudes (Figure 5). This pattern is also evident across bioclimatic zones: the RGI reveals a stronger greening signal in the Polar Desert and Northern Arctic tundra compared with the Arctic Shrub-Tundra (Figure 4), whereas AGI depicts less variation along this ecological gradient.

These findings suggest that the RGI provides complementary information in sparsely vegetated regions where small additions of biomass or plant establishment can generate proportional changes that are ecologically significant, but difficult to detect using the absolute $NDVI_{max}$ trend alone. Conversely, AGI is more suited to areas with well-established vegetation cover where linear changes in canopy structure more directly translate into measurable $NDVI_{max}$ change. This distinction aligns with well-known challenges in detecting vegetation signals in low-productivity environments (i.e., Liu and Treitz, 2016) and the non-linear link between NDVI and biophysical properties (Myers-Smith et al. 2020). In harsh northern environments such as the Polar Desert, limited vegetation cover means that small increases in plant establishment can have significant ecological implications (Høye et al. 2013; Panchen and Gorelick 2015). For example, O'Kane and Henry (2024) showed that even minimal cover increases from 0.53% to 1.74% over 21 years represented a tripling of dominant plant abundance on Ellesmere Island, while having probably limited impact on the radiometric signal at the scale of a Landsat pixel. The RGI approach might provide another interpretation to this vegetation dynamic and the directionality of the succession that is occurring in these sparsely vegetated areas.

Latitudinal greening variations detected by the RGI may also be linked to climate system forcing, including Arctic amplification and coastal changes. Based on CAVM bioclimatic zones, greater RGI-inferred greening in the western Polar Desert, particularly along coasts facing the Arctic Ocean, may reflect the decline in sea ice cover in this sector (Gautier et al. 2022), which can enhance local summer warming, precipitation, and resource availability (Buchwal et al. 2020). These findings agree with the expectation that high-latitude plant communities will react quickly to warming due to strong climate feedbacks at high latitudes (Rantanen et al. 2022). The RGI emphasizes vegetation changes in harsh high-latitude conditions, which complements existing literature that reports restricted absolute greening at high latitudes (e.g., Ju and Masek, 2016). Although AGI values agree with findings from Ju and Masek (2016) and Berner et al. (2023), the RGI reveals distinct latitudinal and ecological gradients (Figures 4 and 5) that highlight changes in northern ecosystems that may otherwise go unnoticed.

The RGI also proves useful for visualizing vegetation change in Polar Deserts, where greening is rarely discussed due to low biomass. While absolute changes remain small relative to lower latitudes, they may influence ecosystem functioning, community assembly, and biogeochemical processes. In such regions, the RGI enabled the detection of small vegetation changes over both spatial and ecological gradients (Figure 4B) that will require further study. At finer spatial scales, however, the AGI may provide a more reliable representation of greening because the RGI can introduce additional noise in heterogeneous terrain. For instance, at the site or regional level—as illustrated on MacKenzie King Island (Figure 3)—AGI sometimes matches closely to known geological deposits. Due to strong latitudinal confounds in the study area, elevation-based greening needs to be interpreted with caution as mountainous areas are predominantly found at northern latitudes in the Archipelago, while southern landscapes are relatively flat. In the higher-latitude regions, vegetation changes may be correlated with other climatic constraints that restrict the species pools (Boulanger-Lapointe et al. 2014), making small greening increments more evident with the RGI. In contrast, AGI tends to highlight vegetation changes in more productive, low-elevation valleys, where greater NDVI increases are required to describe comparable ecological evolution.

Data processing considerations also contributed to differences between the indices. An example is the calculation of RGI, which relies on a baseline estimated from Sen's regression intercept rather than from raw early-series $NDVI_{max}$ values. This approach reduces year-specific noise early in the time series and could lead to a smoother distribution in the RGI histograms (Figure 2D). Despite its benefits, this reinforces the importance of carefully selecting baseline periods and interpreting relative metrics within their methodological context. In our case, we decided to restrict our analysis to pixels presenting baseline NDVI superior to 0.1 to ensure that vegetation was already present at the beginning of the time series (Bayle et al. 2021).

The greening signal is first and foremost a relative measure of the evolution of plant cover and is highly dependent on the initial state of the ecosystem. Beyond greening, both indices identified areas where the $NDVI_{max}$ signal decreased (referred to as browning, Figure 2B), although these represented a small fraction of the total vegetated surface. Browning occurred predominantly near water bodies and on drier elevated plateaus. Multiple drivers may contribute to declines in $NDVI_{max}$, including localized permafrost disturbances such as active-layer detachments or retrogressive thaw slumps (Verdonen et al. 2020), as well as drought stress associated with increased evapotranspiration (Zona et al. 2023). Interpretation remains challenging because sparse, patchy vegetation cover introduces uncertainty in NDVI-based estimates (Davidson et al. 2016). Therefore, approximation of greening with $NDVI_{max}$ is a useful tool but, it is not possible to translate this signal into ecological processes responsible for the observed greening or the primary causes of a browning. Further work is required to explore the ecological information behind NDVI metrics under changing environmental conditions. Significant changes in high-latitude vegetation communities often occur at sub-pixel scales (e.g., shifts in dominant species, functional traits, or soil moisture regimes), making it necessary to integrate higher-resolution remote sensing and ground observations to better distinguish between true ecosystem declines and remote sensing artifacts (Yang et al. 2021).

Overall, using both AGI and RGI provides a more complete representation of vegetation change in the Canadian Arctic Archipelago. The AGI robustly captures absolute greening patterns in well-vegetated areas, while the RGI enhances detection of subtle but ecologically significant gains in low-vegetation high-latitudes ecosystems. Continued monitoring with complementary remote-sensing tools and targeted field validation will be essential to improve our understanding of the processes underlying these vegetation trends and their implications for rapidly changing Arctic ecosystems.

## Conclusion

Our results demonstrate that incorporating a relative greening metric such as the RGI, based on $NDVI_{max}$, provides complementary insight into vegetation change across the Canadian Arctic Archipelago. By emphasizing proportional change, the RGI highlights subtle increases in vegetation cover in high-latitude environments where vegetation is sparse, heterogeneous, and especially sensitive to warming. While the commonly used AGI effectively captures absolute greening patterns in more productive ecosystems, the RGI reveals additional spatial variability in greening along the strong latitudinal gradients of the region. Together, AGI and RGI improve the interpretation of $NDVI_{max}$ as proxies of vegetation change, particularly when applied across the gradient of the Canadian Arctic Archipelago. However, the use of NDVI-based indicators also has limitations. Detecting vegetation change remains challenging in areas with very low cover, steep topographic gradients, glacier forelands, or highly reflective substrates, where the NDVI signal can become noisy or confounded. Furthermore, $NDVI_{max}$ estimates photosynthetic activity but does not directly identify the ecological processes behind the causes of browning or greening. Improved understanding of vegetation responses to shifting environmental conditions—such as lengthening growing seasons, altered soil moisture regimes, and local disturbance events—will require a combination of spectral indicators from remote sensing data with field observations. Using Landsat imagery enabled consistent, long-term monitoring across a vast Arctic region, where medium spatial resolution is critical for detecting ecosystem change. Although this constrains the number of spectral indices that can be used due to sensor characteristics, the length and continuity of the Landsat record offers valuable advantages for assessing multi-decadal vegetation trends. Our study emphasizes the novelty of applying a four-decade Landsat time series to improve our understanding of the greening signals in the Canadian Arctic Archipelago. Our capacity to assess how climate change is changing Arctic ecosystems will be enhanced by a deeper comprehension of the spatial heterogeneity in greening throughout northern bioclimatic zones. As global warming accelerates, integrating multiple indicators of vegetation dynamics can improve our understanding of its impact on the northern regions at the forefront of the consequences of these changes.

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## Authors' contributions

All authors agree with the contents of the manuscript and its submission. E.H.J. and A.R. developed the theoretical framework. E.H.J. performed the calculations and performed the statistical analysis. A.B. contributed to develop the code on Google Earth Engine. All authors contributed to the final version of the manuscript by helping in data interpretation and reviewing the manuscript critically. A.R. supervised the project.

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## Data availability statement

The data that support the findings of this study are from open sources. The availability of the code used for the analyses can be provided by contacting the corresponding author.

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