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Complexity revealed in the greening of the Arctic

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As the Arctic warms, vegetation is responding, and satellite measures indicate widespread greening at high latitudes. This 'greening of the Arctic' is among the world's most important large-scale ecological responses to global climate change. However, a consensus is emerging that the underlying causes and future dynamics of so-called Arctic greening and browning trends are more complex, variable and inherently scale-dependent than previously thought. Here we summarize the complexities of observing and interpreting high-latitude greening to identify priorities for future research. Incorporating satellite and proximal remote sensing with in-situ data, while accounting for uncertainties and scale issues, will advance the study of past, present and future Arctic vegetation change.

The Arctic has warmed at more than twice the rate of the rest of the planet in recent decades[1,2]. Over the past 40 years, satellite-derived vegetation indices have indicated widespread change at high latitudes[3–16,16]. Satellite records allow the quantification of change in places that are otherwise unevenly sampled by in-situ ecological observations[17]. Positive trends in satellite-derived vegetation indices (often termed Arctic greening)[15] are generally interpreted as signs of in-situ increases in vegetation height, biomass, cover and abundance[5,18,19] associated with warming[5,14]. In the most recent report by the Intergovernmental Panel on Climate Change, tundra vegetation change, including greening trends derived from satellite records[20], was identified as one of the clearest examples of the terrestrial impacts of climate change. Large-scale vegetation–climate feedbacks at high latitudes associated with greening could

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alter global soil carbon storage and the surface energy budget[21,22]. In recent years, slowing or reversal of apparent greening from satellite studies has been reported in some regions (sometimes termed Arctic browning)[3,4,12,13,15,23,24]. This slowdown is seemingly at odds with earlier responses to long-term warming trends[3,25]. Research now indicates substantial heterogeneity in vegetation responses to climate change in the Arctic[18,19,26,27]. However, the mechanistic links between satellite records and in-situ observations[3,6,24] remain unclear, owing to conceptual and technical barriers in their analysis and combined interpretation.

A review of Arctic greening

The terms Arctic 'greening' and 'browning' can have different meanings in the remote sensing and ecology literatures. From a remote sensing perspective, 'greening' (hereafter spectral greening) generally refers to a positive trend[4,5,7,8,10,13–15], and 'browning' (hereafter spectral browning) generally refers to a negative trend in satellite-derived vegetation indices[3,4,12,13,15,23,24]. Less frequently, greening is also used to describe advances in the seasonal timing of these vegetation proxies[4,28]. From a field-ecology perspective, greening (hereafter vegetation greening) and browning (hereafter vegetation browning) refer to field-observed changes in vegetation[4,12,13,24]. Historically, the general terms greening and browning were thus used to describe both a proxy of vegetation change and/or vegetation change itself depending on context. This lack of precise usage causes conceptual misunderstandings about Arctic greening and attribution to the drivers of change. Here, we present the current understanding of Arctic spectral and vegetation greening and browning to lay the foundations for a consensus between the remote sensing and field ecology perspectives.

Vegetation indices as proxies of vegetation productivity. Trends over decadal timescales (hereafter 'long-term trends') in global vegetation dynamics are most commonly quantified from time series of spectral vegetation indices derived from optical satellite imagery (Fig. 1). These indices are designed to isolate signals of leaf area and green vegetation cover from background variation by emphasizing reflectance signatures in discrete regions of the radiometric spectrum[6,29–32]. Common vegetation indices include the normalized difference vegetation index (NDVI, Fig. 2a), enhanced vegetation index (EVI) and soil-adjusted vegetation index (SAVI), among others[33–35]. NDVI correlates with biophysical vegetation properties such as leaf area index and the fraction of absorbed photosynthetically active radiation (fAPAR)[14,36–39]. However, these vegetation indices were not developed in polar contexts[40] and are only proxies of photosynthetic activity rather than direct measurements of biological productivity[33,39,41]. NDVI is the most commonly used vegetation index because it is simple to calculate with spectral bands monitored since the launch of early-generation Earth-observing satellites in the 1970s (Fig. 2b) and is perhaps best defined as a measure of aboveground vegetation greenness.

The longest-term openly available NDVI datasets have been produced from satellite-based sensors with broad spatial coverages and different sampling frequencies. The most common datasets include: (1) the Advanced Very-High-Resolution Radiometer (AVHRR; 1982 to present) on board NOAA satellites; (2) the Moderate-resolution Imaging Spectroradiometer (MODIS; 2000 to present) on board NASA satellites; and (3) NASA–USGS Landsat sensors (1972 to present). Most studies of long-term trends calculate annual measures of maximum NDVI to derive change over space and time, although time-integrated approaches are also used[30,42–44]. However, trends in NDVI data produced from different satellite datasets or using different methods do not always correspond at a given location[6,45,46] (Fig. 1a,c). Thus, it can be challenging to distinguish ecological change from differences due to methods and sensor/platform-related issues when interpreting localized spectral greening or browning signals (Table 1, Fig. 2).

Ecological factors. The ecological processes underlying spectral greening or browning measured by satellites are diverse and may unfold across overlapping scales, extents and timeframes. In tundra ecosystems, vegetation changes linked to spectral greening could include: encroachment of vegetation on previously non-vegetated land surfaces[18,47]; changes in community composition such as tundra shrub expansion[5,19,27]; and/or changes in plant traits such as height[48,49], leaf area or phenology[50–52]. Tall shrub tundra typically has a higher NDVI than other tundra plant types[49,53,54], and bare ground[29] has a much lower NDVI than vegetated tundra (Fig. 2a). Spectral browning could be related to various factors including, for example, loss of photosynthetic foliage[12] or increases in bare ground cover due to permafrost thaw[55] (Fig. 1g). Thus, changes in the species composition, growth form and traits of plant communities can influence greening and browning trends.

Physical factors. Widespread non-biological changes in high-latitude ecosystems could confound and decouple spectral greening or browning trends from changes in plant productivity (Table 1). Land cover, topography and associated soil moisture, surface water, land-surface disturbances and snowmelt dynamics can all influence the measured spectral greenness of landscapes[56–63] and are likely to influence greening trends. For example, changes in the extent of summer snow patches[63], surface water[60] or surface soil moisture[59] that are often associated with landscape-scale topographic variation could influence the measured NDVI of the land surface. At high latitudes, optical satellite sensors are only effective for a short annual window because of the prolonged polar night, whereas low Sun angles and persistent cloud cover reduce data quality in the summer season (Table 1). The unique physical properties of high-latitude ecosystems in addition to the constraints of polar remote sensing are often underemphasized in remote-sensing studies of Arctic vegetation change.

Arctic browning and heterogeneity of spectral greening trends. Not all areas of the Arctic are spectrally greening (Fig. 1), and in recent years spectral browning and heterogeneity of spectral greening trends have been highlighted[3,4,12,13,23]. Ecological explanations for vegetation browning include the sudden loss of photosynthetically active foliage due to extreme climatic events[64–67], biological interactions (such as disease or herbivore outbreaks)[68–70], permafrost degradation[23,55] (Fig. 1g), increases in standing dead biomass[71], coastal erosion[72], salt inundation[73], altered surface water hydrology[74,75] or fire[9,76,77]. Spectral browning, however, could be attributed to reduced productivity caused by adverse changes in growing conditions such as lower water availability, shorter growing seasons[3] or nutrient limitation[27]. Nonetheless, long-term spectral greening trends remain far more pervasive than spectral browning in tundra ecosystems. Figures vary from 42% greening and 2.5% browning from 1982 to 2014 in the GIMMS3g AVHRR dataset[78] to 20% greening and 4% browning from 2000 to 2016 in Landsat data[15], and to estimates of 13% greening and 1% browning for the MODIS trends calculated for 1,000 random points in the tundra polygon in Fig. 1c from 2000 to 2018. At circumarctic scales, the magnitude, spatial variability and proximal drivers of patterns and trends of spectral greening versus browning are not well understood.

Correspondence between satellite-based and ground-based observations. Evidence for correspondence among in-situ vegetation change and trends in satellite-derived vegetation indices is mixed[47,79–81]. NDVI trends across satellite datasets do not necessarily directly correspond with one another[6,9], nor does any one sensor or vegetation index combination correspond directly

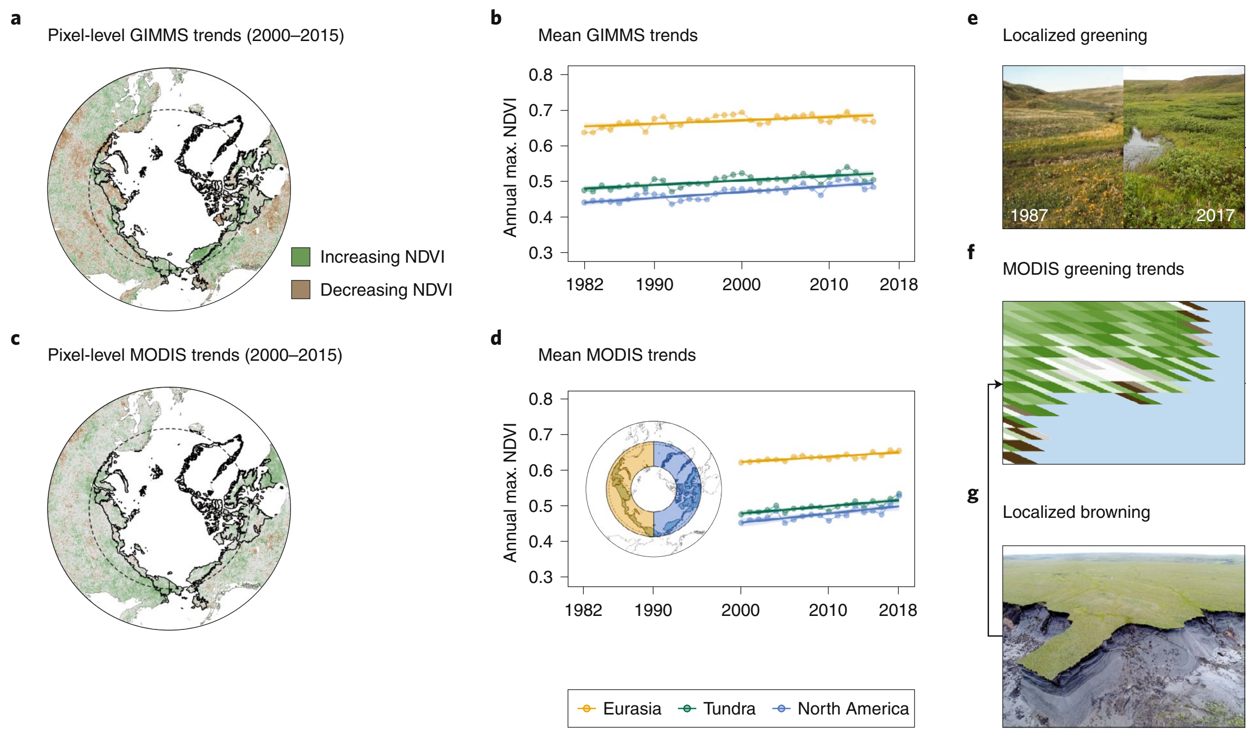

Fig. 1 | Satellite records indicate greening trends across the circumpolar Arctic. Apparent Arctic greening, which varies across space and time and among satellite datasets, is driven both by actual in-situ change and, in part, by challenges of satellite data interpretation and integration. **a**–**d**, Trends in maximum NDVI vary spatiotemporally, and the magnitude of changes depends on what satellite imagery is analysed (**a** and **c**, data subsetted to temporally overlapping years; **b** and **d**, data from the Global Inventory Modeling and Mapping Studies dataset from AVHRR (GIMMS3gv1) 1982 to 2015, and MODIS MOD13A1v6 2000 to 2018). **e**–**g**, Regional trends may summarize localized greening, for example shrub encroachment (**e**) and browning such as permafrost thaw (**g**) occurring at the pixel scale on Qikiqtaruk–Herschel Island in the Canadian Arctic (**f**). NDVI trends (**a** and **c**) were calculated using robust regression (Theil–Sen estimator) in the Google Earth Engine[130]. Dashed line indicates the Arctic Circle, and the black outlined polygon (**a** and **c**) and green 'tundra' line (**b** and **d**) indicate the Arctic tundra region from the Circumpolar Arctic Vegetation Map (www.geobotany.uaf.edu/cavm/). The inset map in **d** indicates the regions for the mean trends for yellow 'Eurasia' and blue 'North America' polygons.

with in-situ vegetation change[47]. For example, NDVI has been related to interannual variation in radial shrub growth[5,10,82], yet how radial growth links to change in leaf area, aboveground biomass or landscape measures of productivity is not always clear[83–85] (Fig. 3). AVHRR NDVI greening trends did not correspond with the lack of change observed with Landsat NDVI data and in-situ plant composition between 1984 and 2009 in northeastern Alaska[47]. Direct comparisons of productivity changes from vegetation cover estimates[18,86], biomass harvests[53] or shrub growth[87] are complicated by the lack of annual-resolution in-situ data and/or low sampling replication across the landscape. We attribute the mixed evidence for correspondence between in-situ and satellite-derived measures of tundra vegetation change and greening to the complexities of existing terminology, challenges of interpretation of spectral vegetation indices at high latitudes, and the scaling issues as outlined below.

In addition to productivity analyses, changes in growing season length and advances in plant phenology have been documented using both satellite[43,78,88–91] and ground-based datasets, and here also paired comparisons do not always correspond (Fig. 4a,b). Measures of longer growing seasons have been attributed to earlier snowmelt and/or earlier leaf emergence in spring[92], and longer periods of photosynthetic activity or later snowfall in autumn[93]. However, few studies have monitored both leaf emergence and senescence of tundra plants in situ, and so far they provide no evidence for an increasing growing period at specific sites[94,95]. In addition, community-level analyses indicate shorter flowering season lengths around the tundra biome[50]. Shifts in plant phenology with warming[50] could also be linked to changing species composition or diversity[18,48,86], thus influencing the phenological diversity across the landscape[96,97]. Satellite records may not capture the ecological dynamics of vegetation phenology at high latitudes, as snow cover can obscure the plant seasonal signal, and deciduous plants make up only a portion of the vegetated land cover. Thus, uncertainty remains over whether satellite-derived changes in circumarctic phenology represent a longer snow-free period uncoupled from the vegetation response or an actual longer growing season of plants (Fig. 4a,b) [94,98–100].

Clarifying the terminology

To distinguish spectral greening and browning events from longer-term trends, we propose clarified definitions of events and trends.

For an individual pixel, we define the spectral trend as an increase or decrease in NDVI (or other spectral vegetation index) over decadal timescales, and a spectral event as a temporal outlier in the vegetation index relative to the long-term trend. Trends should be determined using a Theil–Sen estimator or similar robust statistical test for analyses of satellite data[30,101].

We define a spectral greening trend as an increase of the vegetation index over decadal timescales. In situ, we interpret a vegetation greening trend as improved conditions for photosynthesis, reduced resource limitation and/or positive responses to disturbance in plant communities, resulting in greater aboveground biomass, leaf area, productivity or changes in plant community composition. We define a spectral browning trend as a decrease in the vegetation index over decadal timescales. A vegetation browning trend may correspond with an in-situ change in vegetation productivity

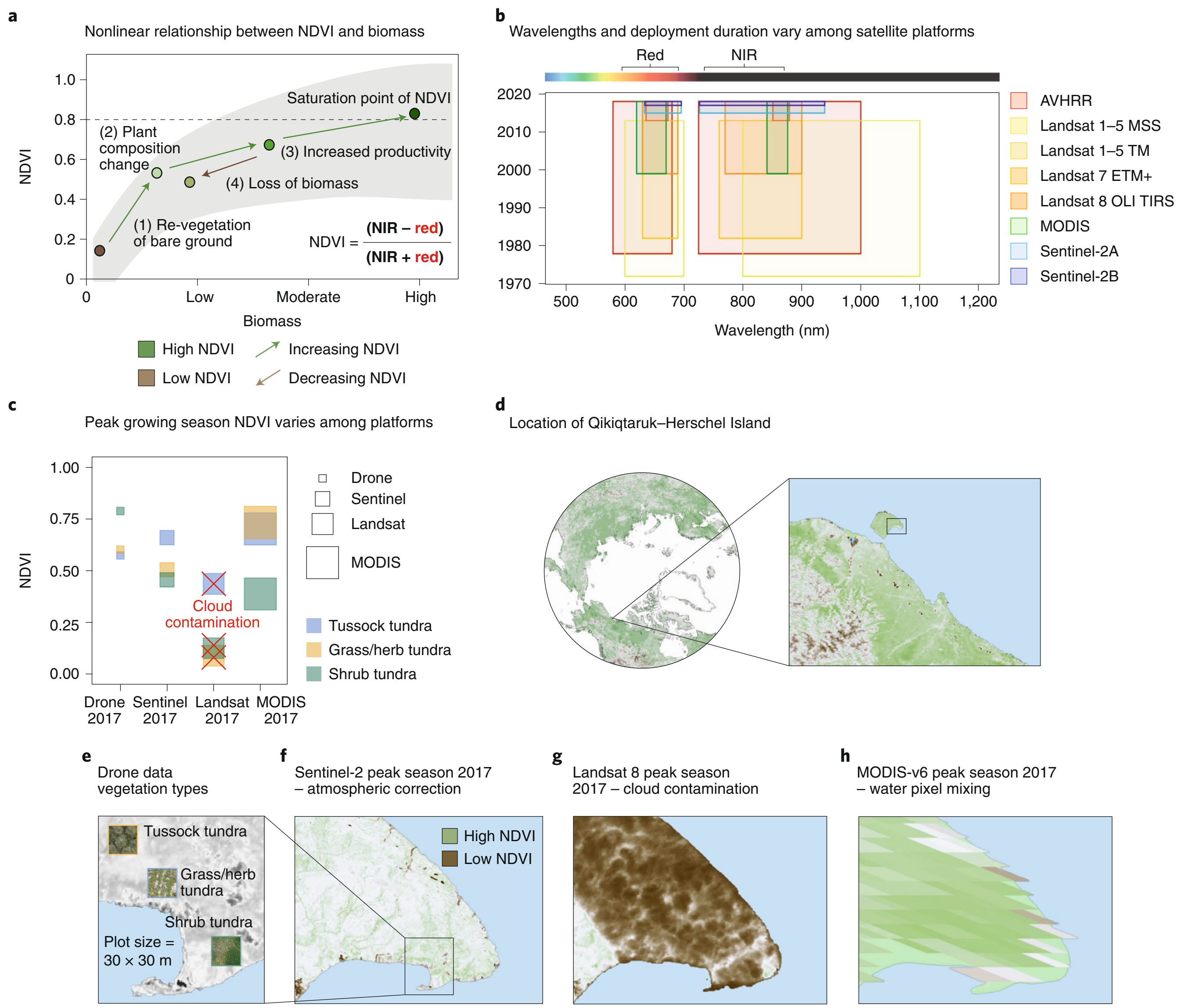

Fig. 2 | Ecological interpretation of trends in NDVI requires a consideration of non-ecological factors. NDVI can vary across datasets owing to NDVI biomass relationships, bandwidths of sensors and data quality issues. **a**, NDVI, calculated as the difference between red and near-infrared (NIR) bands, has a nonlinear relationship with several common metrics of plant productivity, such as biomass and leaf area index. **b**, Satellite platforms have different spectral bandwidths, which can influence calculations of NDVI despite shared centre wavelengths. **c**–**h**, NDVI values from commonly available satellite data products and drone datasets (**c**) differed substantially across products and across plots of three different vegetation types (**e**) during the period of peak biomass in 2017 on Qikiqtaruk–Herschel Island, Yukon (**d**). Here, factors such as a lack of atmospheric correction (**f**), cloud or fog contamination (**g**), sub-pixel mixing (**h**), different plot grain sizes of data in more or less heterogeneous vegetation cover, and timing of data acquisition could have all influenced the NDVI values. Data were analysed and extracted for all overlapping pixels in 30 m × 30 m plots from 13 July 2017 to 4 August 2017 using the Google Earth Engine[130] for the MODIS MYD13A1v6 (**h**; pixel size 500 m × 500 m) and Landsat 8 (**g**; pixel size 30 m × 30 m) NDVI products, and the top-of-atmosphere Sentinel-2 NDVI product without atmospheric corrections (**f**; pixel size 10 m × 10 m). Pix4D-processed drone data (in **c**) were collected using a radiometrically calibrated four-band multispectral sensor (Sequoia, pixel size 12 cm × 12 cm) on an FX-61 fixed-wing platform with the High-latitude Drone Ecology Network protocols (https://arcticdrones.org/). We purposely present data with quality and processing issues above to highlight the challenges in quantifying NDVI in regional-to-global studies where data quality issues may be spatially or temporally variable among locations. ETM+, Landsat's Enhanced Thematic Mapper Plus; OLI, Operational Land Imager; TIRS, Thermal Infrared Sensor; TM, Thematic Mapper.

due to plant dieback or loss of vegetation cover through biotic or abiotic disturbances.

We define spectral greening events as short-term increases in vegetation index greenness that can be attributed to an ecological process such as revegetation of ground cover after fire and spectral browning events as short-term decreases in the vegetation index that can be attributed to a disturbance such as permafrost thaw or plant dieback.

The definitions that we propose here distinguish between slower-acting climatic or biotic drivers of greening or browning trends, and event-driven changes caused by weather, biotic pulses or other regional events such as fire.

Differentiating events and trends. In any measure of remotely sensed or field-based greening, separate consideration of trends and events will increase ecological interpretability (Fig. 5b).

Table 1 | Factors influencing the magnitude and direction of change in vegetation indices

Factors influencing vegetation indices	Specific effects	Influence on apparent greening patterns and trends
Low Sun angle	Radiometric effects	At high latitudes, low Sun angles and cloud shadows can have a greater influence on vegetation indices than at lower latitudes[62]. NDVI varies with Sun angle, an effect magnified in spring and autumn[62]. Shadows also reduce NDVI and may be difficult to detect in coarse-grained imagery[44].
Cloud cover	Radiometric effects Spectral mixing Adjacency effects	Thin cloud, fog and smoke can influence imagery, reducing NDVI. Cloud and fog are particularly problematic in coastal regions and can vary greatly between image acquisitions[44]. Cloud-screening algorithms differ among satellite datasets (in part as a function of available spectral bands), and partly cloudy or hazy conditions are particularly difficult for screening algorithms to detect consistently. In addition, the fogginess of Arctic locations can vary over time owing to changing temperatures[44] and/or sea ice conditions[124].
Standing water	Spectral mixing Adjacency effects	Standing water[60] can influence comparisons of vegetation indices across space and may not be detectable in coarse-grained imagery, despite influencing spectral signatures. NDVI values of water are generally low, but shallow water or standing water intermixed with vegetation or algal growth may not be identified as water by quality filters and may have higher NDVI. Water within a pixel may lead to artificially low NDVI values and can influence estimates of NDVI change over time. This is especially relevant to the Arctic during the spring and summer, as snow melts and turns into ephemeral ponds and lakes whose spectral signatures will be mixed with nearby vegetation[125]. NDVI signals could be driven by changes in standing water over time associated with changing precipitation, permafrost conditions and/or warming, rather than by changes in vegetation[56,57,60,125,126].
Snow patches	Spectral mixing Adjacency effects	Sub-pixel-sized snow patches will decrease the NDVI for a given tundra area[57]. NDVI values of snow are strongly negative. Earlier snow loss or later snow return may drive a strong positive trend in NDVI. Longer persistence of snow on the landscape in patches may not be filtered by quality algorithms, yet could still lead to lower NDVI values.
	Snow versus phenology dynamics	Surface reflectance just after snow-off is commonly used as the baseline when fitting phenology models. This approach masks the effects of subnivean phenological progression and/or may overemphasize the role of snow-off or snow-on dates as a driver of plant phenology[57,63].
Soil moisture	Spectral mixing	Soil moisture can influence the reflectance of vegetated tundra surfaces[58,59]. NDVI values are sensitive to soil moisture, which may or may not co-vary with vegetation change[125]. Furthermore, NDVI is relatively insensitive to vegetation changes in very sparsely vegetated (for example the High Arctic[127]) and very densely vegetated (for example forest or shrubland[128]) environments.
	Plant water content	Mosses can absorb water and thus influence surface reflectance of landscapes independent of vascular plant phenology and productivity[126].
Short growing season	Timing of image acquisition	Trends in NDVI metrics and growing season length can be influenced by the timing of data acquisition. To compare spatial patterns in vegetation indices among sites, images are required from the same time within the growing season and the same time points within the day[126]. However, the short growing seasons at high latitudes make image acquisition particularly challenging. Satellites have different temporal frequencies for overpasses, thus influencing comparisons. Length of growing season decreases at higher latitudes, and thus the impact of missing data is of greater magnitude as latitude increases.
Rapid plant phenology	Chosen phenometric	The specific metrics used to quantify phenology will influence the patterns observed[91]. Combining datasets with different spatial and temporal resolutions can limit comparisons (Fig. 2). Variation in phenology metrics due to curve-fitting methods can exceed variation in measured phenology signals. Thus, using the same phenological functions across large geographical and ecological gradients, such as across the high latitudes, may introduce biases and/or errors.
	Phenological diversity	Changes in phenology of individual species or plants growing in particular microclimates can lead to shifts in landscape phenology[50].
Plant traits and functional groups or types	Isolating changes in plant productivity and canopy structure versus composition	Vegetation indices are related to radiation absorbed by green foliage (APAR), canopy structure, species composition, leaf-level traits and biomass[37,39] (Fig. 2). However, how vegetation indices and ecological properties covary across diverse Arctic ecosystems is not well established. Other factors, including bare ground cover, canopy structure and so on, that influence vegetation indices must be accounted for to isolate productivity change from other land surface changes.
	Vascular and deciduous versus non-vascular and evergreen plants	Non-vascular or evergreen plants can obscure the deciduous vascular plant seasonal signal[49,81]. Tundra without vascular plants can additionally have a substantial cover of biological soil crust communities consisting of lichens, cyanobacteria, mosses and green algae that may also influence NDVI[107,126].

Various geophysical[13,106,129], environmental[44,60,61] and ecological[12,47,49,54,57,110] factors can influence the magnitude and direction of change in vegetation indices and are particularly problematic at high latitudes[6]. The effects include the following. (1) Radiometric effects: differences among satellite datasets including bandwidths, atmospheric effects, cloud-screening algorithms, sensor degradation, orbital shift and bidirectional reflectance distribution functions originating from differences in field of view and Sun geometries. (2) Spectral mixing: the blending of sub-pixel spatial heterogeneity that can influence the overall pixel signal (Fig. 2). (3) Adjacency effects: the reflectance of surrounding pixels that can influence the signal of a given pixel (Fig. 2). (4) Various environmental and ecological factors, from snowmelt and soil moisture dynamics to composition of evergreen versus deciduous or vascular versus non-vascular plants.

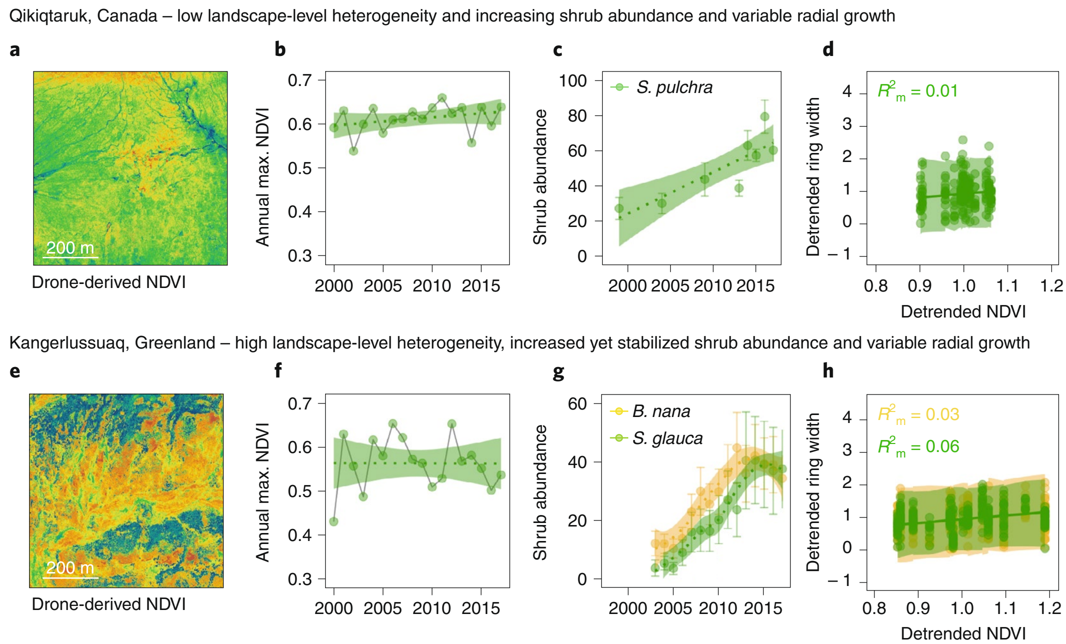

Fig. 3 | Spatial heterogeneity in landcover can influence NDVI–vegetation relationships. Sub-pixel spatial heterogeneity in vegetative greening and browning cannot be accurately captured at coarser grains. **a**–**h**, Landscape patterns (**a**, **e**), trends (**b**, **f**) and variability (**d**, **h**) in NDVI may not represent in-situ observations of vegetation change. NDVI trends and interannual variability had mixed correspondence with increases in shrub abundance (**c**, **g**) and interannual variability in shrub growth on Qikiqtaruk–Herschel Island, Yukon[94] (**c**, point framing in 12 plots, each 1 m^2; **d**, *Salix pulchra*, $n = 21$, https://github.com/ShrubHub/QikiqtarukHub) and Kangerlussuaq, Greenland[84,131] (**g**, 13 plots, each 0.25 m^2; **h**, *Betula nana*, $n = 42$, and *Salix glauca*, $n = 32$, https://arcticdata.io/catalog/view/doi:10.18739/A24X0Q, https://arcticdata.io/catalog/view/doi:10.18739/A28Q18, https://arcticdata.io/catalog/view/doi:10.5065/D6542KRH). Errors are standard error bars around mean values (**c**, **g**) and 95% credible intervals for a Bayesian hierarchical model of the relationship between detrended annual growth rings and NDVI, with shrub individual and year as random effects (**d**, **h**). Detrending was done using a spline fit from the dplR package in R. Credible intervals for model slopes overlapped with zero (**d**, **h**). Marginal R^2 values indicate the variance in detrended ring widths explained by detrended NDVI (**d**, **h**). Landscape NDVI patterns (**a**,**e**) were measured using a Parrot Sequoia and FX-61 fixed-wing platform according to High-latitude Drone Ecology Network protocols in the summer of 2017 (https://arcticdrones.org/) and analysed using the Pix4D software. Coarser-grain NDVI time series (MODIS MOD13A1v6, 500-m pixels) were calculated using Google Earth Engine[130] and the Phenex package in R[132].

Spectral greening and browning trends operate at any spatial scale, from localized patches to landscapes or even biome extents over decades. In contrast, spectral greening and browning events, such as those caused by vegetation dieback or rapid vegetation increase after disturbance, are often restricted to patch and regional scales over shorter durations. Events often have more limited extents than trends, owing to their proximal causes, such as changes in herbivory or precipitation. Broader-scale events are also possible (for example, globally synchronized reductions in vegetation productivity caused by changes in insolation related to an intense volcanic eruption[102]). Therefore, greening or browning events might be embedded within overall spectral greening or browning trends, both temporally and/or spatially, without necessarily driving them (Fig. 5b). Examining the trend direction, magnitude and variance around the fit over time can shape more detailed investigations into the ecological interpretation of Arctic spectral greening trends.

Influence of baselines and temporal sampling. The baseline to which we compare productivity change will influence our interpretation of trends[103]. Spectral greening or browning trends and events may result in threshold changes where on-the-ground productivity does not return to the longer-term baseline (Fig. 5b; for example, pulse in recruitment at treeline[104] or shrubline[105], or a large fire[77]). In both satellite datasets and field observations, the baseline conditions are often constrained by the limitations of data availability rather than any deliberately selected starting point[6]. The low temporal sampling frequency of a few days to a few weeks of many legacy remote-sensing datasets (for example AVHRR, MODIS or Landsat) also introduces temporal scale-dependent effects that may be magnified in Arctic systems (Table 1). For example, comparisons of phenology across latitudes can be less reliable at higher versus lower latitudes, owing to shorter growing seasons and therefore fewer satellite data collection points for use in change detection analyses[42,88,89]. Metrics based on the annual maximum NDVI of a given pixel are more likely to be influenced by temporal sampling artefacts at high latitudes than those that integrate productivity estimates through time, such as the growing-season-integrated NDVI (GSINDVI)[42], time-integrated NDVI (TiNDVI)[43] or early growing-season-integrated NDVI indices[44]. Trends in either instance could be observed or not observed for statistical reasons related to sample size and/or the strength or linearity of the trend. Thus, simple linear analyses of annual greenness metrics derived from satellite data may not always capture real-world ecological change (Fig. 5b).

Challenges in the interpretation of vegetation indices. In addition to the need for more clearly defined terms, challenges remain in the ecologically meaningful interpretation of long-term trends in optical satellite data, especially at high latitudes. The statistical relationship between a vegetation index and biomass, leaf area, phenology or any other measures of productivity can vary owing to a suite of intrinsic (for example sensor design or quality flagging algorithms), extrinsic (for example atmospheric conditions, Sun angle or snow cover)[6,106] and biological factors[107] (Table 1).

As an example, the centre wavelength and width of spectral bands (for example, in the red or near-infrared) used to generate vegetation indices were designed for different purposes in different

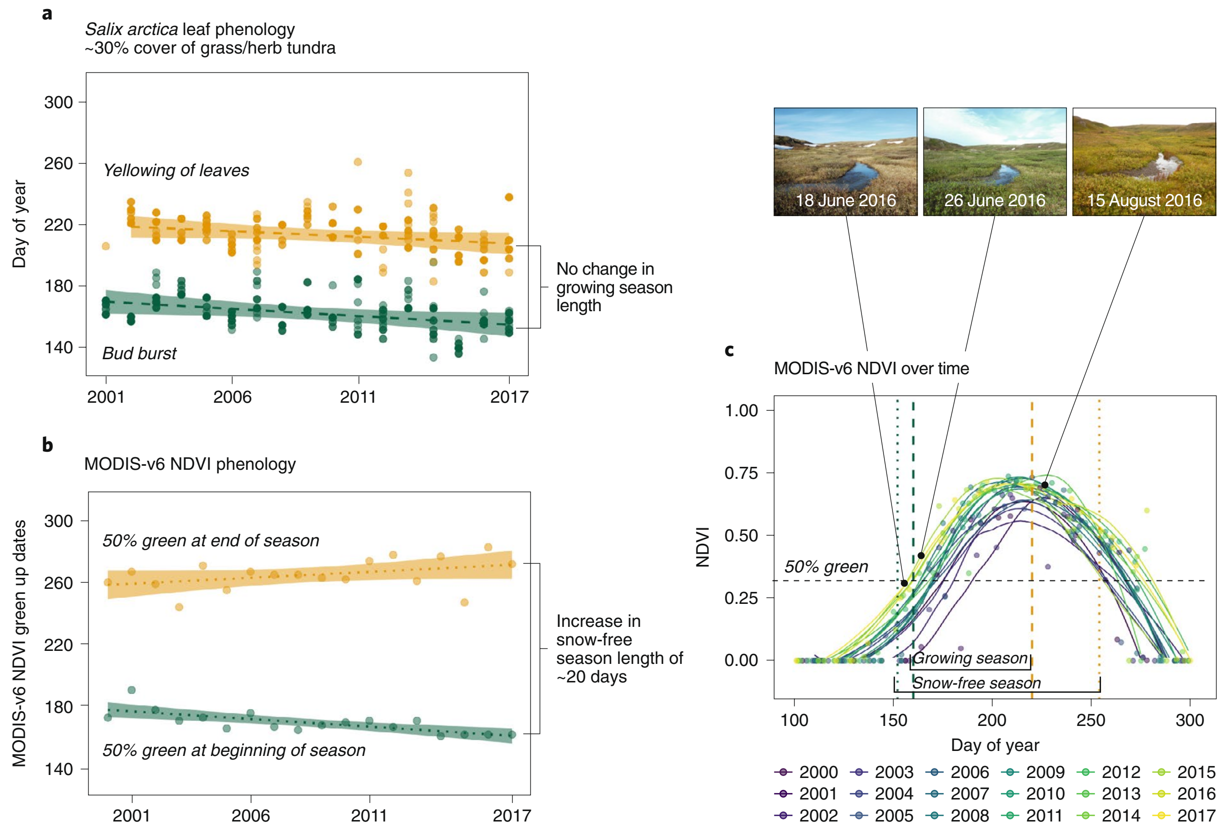

Fig. 4 | Satellite-derived estimates do not always match in-situ observations of plant phenology across the growing season. a–c, Satellite-observed snow-free season length of the land surface (here defined as the period with NDVI greater than 50% of the max NDVI, **b** and **c**) might not directly correspond to the growing season of vascular plants in tundra ecosystems, particularly in autumn (**a**). Snowmelt dynamics can obscure the plant phenology signal, and non-vascular or evergreen plants can obscure the deciduous vascular plant seasonal signal. Plant phenology data were collected at 20 monitoring plots on Qikiqtaruk–Herschel Island for the species *Salix arctica*, which makes up approximately 30% of the cover in the grass- and forb-dominated vegetation type. Analyses indicate that both leaf emergence and senescence have become earlier, resulting in no change in realized growing season length despite substantial increases in the snow-free period of the land surface[94] (**a–c**, https://github.com/ShrubHub/QikiqtarukHub). Satellite data are MODIS MOD13A1v6 extracted for the pixel containing the phenology transects using Google Earth Engine[130] and the Phenex package in R[132] (**b** and **c**).

sensors (Fig. 2b). Although the NDVI formula may be the same, the covered spectral wavelength ranges differ between datasets[108] (Fig. 2a,b). Thus, the datasets may be more or less sensitive to specific non-vegetative influences, such as atmospheric scattering or the magnitude of spectral mixing associated with non-vegetated surfaces[57]. Spectral unmixing is the process of decomposing the spectral signature of a mixed pixel into the abundances of a set of endmember categories[109]. Longer-term vegetation change is difficult to resolve from cross-sensor comparisons among different satellite datasets or even among intercalibrations of the same sensor type (Fig. 1).

For these reasons, caution is warranted when comparing vegetation indices derived from different satellite products or even versions of the same product with different atmospheric corrections, quality assessments and spatial/temporal compositing approaches[6,108]. Differences in NDVI signal processing are actively studied by the remote-sensing community (Table 1) but could be better accounted for or quantified in Arctic greening studies.

Nonlinearities in NDVI as a vegetation proxy. Direct interpretations of vegetation changes from spectral data are contingent on the local relationship between NDVI and in-situ vegetation. The statistical relationships between vegetation indices and measures of Arctic vegetation biomass are nonlinear[29,110] (Fig. 2a). This nonlinearity presents challenges for trend interpretation that are illustrated in Fig. 2a. Here, an absolute increase in biomass for a 'low-biomass' community towards a 'moderate-biomass' community would result in a positive NDVI trend, but that same absolute biomass increase from moderate to high biomass would show virtually no trend in NDVI, owing to saturation (Fig. 2a). Thus, the relationship to common ecological variables such as changes in biomass or shrub ring widths (Fig. 3c,d,g,h) can be obscured by nonlinearities. Because the greening and browning terms are tied to changes in vegetation proxies, rather than direct biological measures, a lack of correspondence could occur between remotely sensed vegetation proxies and in-situ vegetation change (Figs. 2, 4 and 5). Such potential discrepancies exemplify why caution should be used when interpreting linear trends in proxies like NDVI (Fig. 1) that are nonlinearly related to vegetation productivity, without the use of in-situ data to corroborate conclusions.

Scaling issues in Arctic greening analyses. Scale and hierarchies present a longstanding challenge in the interpretation of remotely sensed vegetation proxies[111–113] (Fig. 5a). All long-term vegetation proxy time series (Landsat, MODIS, AVHRR) spatially aggregate spectral data to pixels (that is, grains) that span hundreds of square metres to tens of square kilometres. The spectral signatures of plants and non-vegetative features in a landscape are reduced to a single

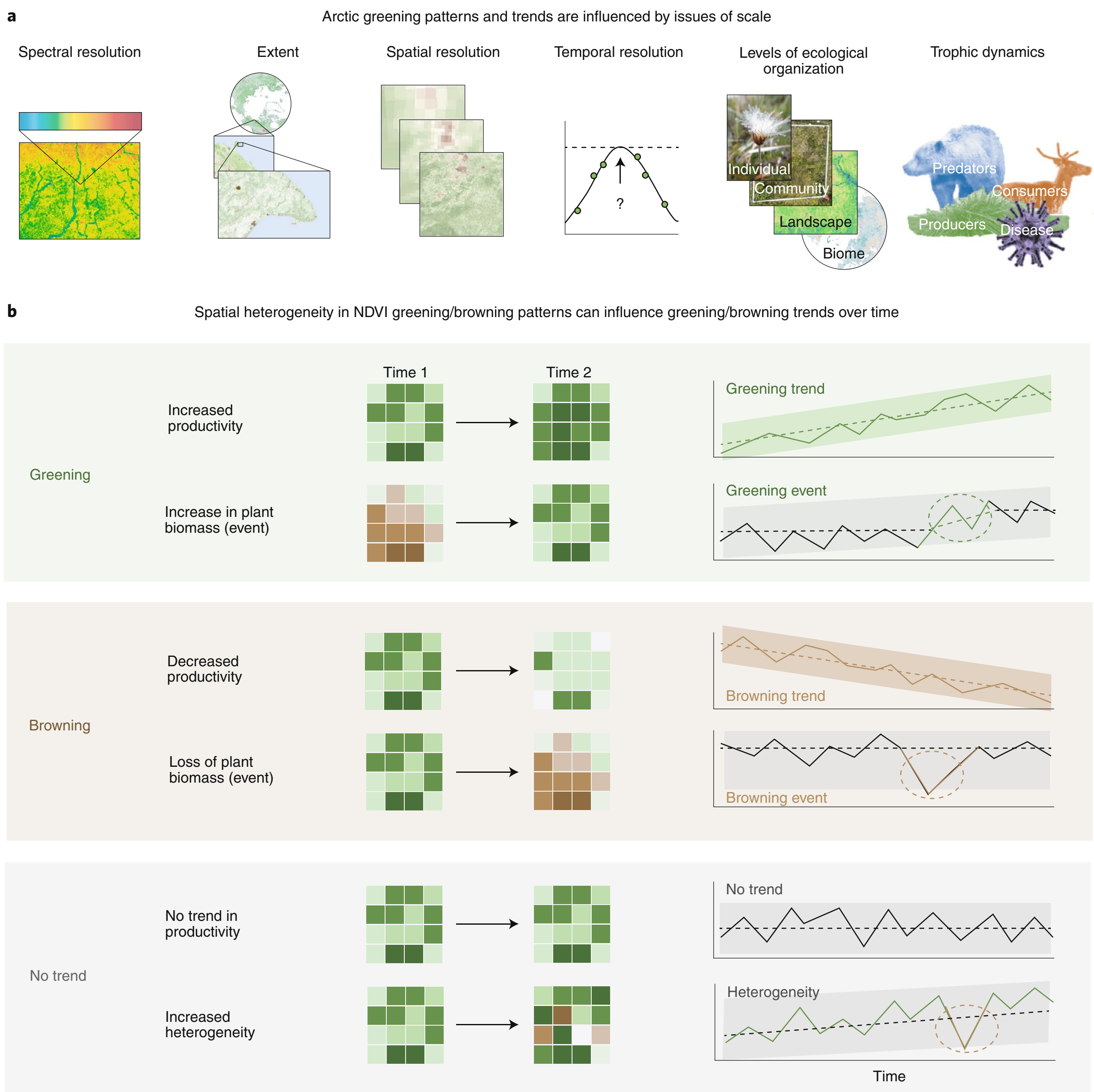

Fig. 5 | Arctic greening is influenced by issues of measurement scale and inference across ecological hierarchies. Spectral greening and browning complexity can be addressed by incorporating scale and clarifying ambiguity in terminology. **a**, Spectral resolution (Fig. 2b), extent (Fig. 1), spatial resolution (Fig. 2), landscape-level heterogeneity (Fig. 3a,e), temporal resolution (Fig. 4c) and ecological factors all influence the interpretation of greening trends. **b**, Within-pixel changes in land surface greening and browning events and trends can translate into different greening and browning patterns as their effects are scaled up. Ecological processes that comprise greening and browning trends include a combination of events, such as a pulse of plant recruitment or growth, a dieback of plants due to an extreme winter climate event, herbivore or disease outbreak or other disturbance and subsequent recovery. Longer-term change such as increasing shrub cover/height or progression of permafrost disturbances can also influence real-world NDVI time series. These different factors add complexity to the interpretation of Arctic greening trends. The scale and hierarchy of observations need to be incorporated into and/or accounted for in future analyses of Arctic greening (Fig. 5a).

value. The loss of variability within pixels masks information useful for the attribution of greening signals to processes across ecological hierarchies from populations and communities to ecosystems (Table 1, Figs. 3 and 5). For example, within a single AVHRR GIMMS3g pixel, a subselection of 1 × 1 km pixels are upscaled to 8 × 8 km (ref. [32]). Within this aggregated pixel, ecological contributions to spectral greening signals, such as increased shrub cover on south-facing slopes or revegetation of drained lake beds, may be mixed with browning signals from, for example, disturbances such as retrogressive thaw slumps or vegetation trampling by herbivores (Fig. 1g). High-latitude pixels may also contain shadows caused by low Sun angle, patchy snow and/or cloud-cover (Table 1). Thus, the emergent time series from such a pixel describes no single vegetation dynamic or environmental factor, but rather their integrated spectral responses. Broad-scale patterns of spatial variability in greening and browning across pixels are also influenced by grain size[113]

(Figs. 1, 2, 5). Finer-resolution satellites such as Landsat can reduce but not necessarily eliminate such spectral mixing[15]. However, the extent to which the sometimes-contradictory greening and browning signals found across different spectral datasets can be attributed to the influence of the scale of measurement is not well quantified.

Complexities of capturing phenology. Measuring landscape phenology with satellite data presents additional challenges to ecological interpretation of Arctic greening (Table 1). The variability of timing of satellite imagery from year to year particularly at high latitudes[91] can confound measures of phenology (known as phenometrics). Cloud or fog cover is highly variable and sensitive to changing sea-ice conditions in coastal Arctic sites[44]. Seasonal variation in cloud and fog cover influences both data availability and image compositing approaches in many phenology products[91]. In addition, vegetation metrics from early spring are much more likely to be influenced by snow, standing water or low Sun angle than those closer to peak biomass in mid- to late summer[8,54,59]. However, early spring is a critical period for establishing a baseline for curve fitting or thresholding used to derive phenometrics. Ultimately, no phenometric is best suited to all Arctic environments or time periods[114]. Snow regimes and land cover variability differ annually and regionally, and thus phenometrics using coarse-grain imagery integrate different abiotic and biotic signals at different points in space and time[114]. Phenological differences of days to weeks or even months can result from analyses using different methods and metrics for the same datasets at the same location[115]. These relative differences are of substantial ecological importance given the short growing seasons of the Arctic[78,114] (Fig. 4). Circumarctic analyses of vegetation indices generally indicate that phenological shifts in the spectral greenness of the land surface are widespread[78,88–90]. However, the magnitude and extent of spatial and temporal scaling issues in high-latitude remotely sensed phenology trends warrant further consideration and research[112].

Towards a consensus perspective on Arctic greening

The fields of remote sensing and field-based ecology will benefit from jointly addressing the complexities of interpreting spectral and vegetation greening and browning trends. Analyses from one satellite platform or one specific ecological context are not sufficient to disentangle Arctic greening complexity. The required next steps will be an integration of perspectives and approaches through existing and new international research efforts to address the following critical research gaps.

Addressing scale issues by integrating proximal remote sensing and in-situ observations into circumarctic greening analyses. Analyses of observations across scales will allow us to bridge the gap and improve our mechanistic understanding of the links between in-situ vegetation dynamics and broader remotely sensed patterns and trends. New instruments for carrying out in-situ and proximal remote-sensing observations for comparison with satellite data are developing rapidly. However, we must urgently develop standardized protocols for field data collection. To aid future synthesis, we need to incorporate data from long-term ecological monitoring[12,18,86,94], historical imagery[116], phenocam networks[117], flux towers[118], high-resolution imagery such as from aircraft, towers and drones[119], and satellites.

Incorporation of heterogeneity and uncertainty into analyses to improve confidence in detection of Arctic greening trends. New data with finer spatial or temporal resolution will inform analyses of historic greening trends. Current circumarctic Landsat analyses are shedding light on greening trends by exploiting data with finer spatial resolution while accounting for the lower temporal resolution of observation records[15]. Recent and ongoing release of finer-resolution satellite datasets (for example from EU-funded Sentinel missions, or the commercial DigitalGlobe or Planet constellations) and data products (for example the Arctic Digital Elevation Model[120]) will provide finer spatial (2–10 m) and/or temporal resolution (1–5 days) data across the Arctic[121]. We can gain a better understanding of past spectral greening signals from legacy satellite datasets by conducting standardized reprocessing with, for example, statistical methods incorporating uncertainty in observations such as image quality information, improved atmospheric corrections and snow detection.

Inclusion of new observational tools beyond optical vegetation indices to clarify the mechanistic links between spectral greening and vegetation change. In addition to incorporating finer-resolution datasets, new types of data collection can inform our understanding of what greening patterns and trends represent. Emerging remote sensing campaigns using hyperspectral sensors or those that can measure solar-induced fluorescence[122] will provide new insights into vegetation dynamics. However, future sensor development across satellite, aircraft and near-surface platforms should be designed to maximize comparability. In addition to new data collection, new approaches to data integration, for example those employing machine learning, will provide greater insights into biome-scale analyses linking remote-sensing observations with ecological change in high-latitude ecosystems[21,123].

Conclusions

Recent research has highlighted the complexity in observed Arctic greening and browning trends. Although satellite data have been used to detect and attribute global change impacts and resulting climate feedbacks in Arctic ecosystems[20,22], numerous questions and uncertainties remain. The three main challenges in resolving these uncertainties are: (1) improving the clarity of the definitions of widely used terminology associated with greening and browning phenomena; (2) promoting the understanding of the strengths and limitations of vegetation indices when making ecological interpretations; and (3) better incorporating and accounting for different scales of observation and uncertainty in analyses of changing tundra productivity and phenology. New sensors and better access to legacy data are improving our ability to remotely sense vegetation change. However, new data alone will not provide solutions to many of the longstanding conceptual and technical challenges. The complexity of Arctic greening will only be fully understood through multidisciplinary efforts spanning the fields of ecology, remote sensing, Earth-system science and computer science. As a field, we need to look forwards to quantify contemporary and future change, but also backwards by conducting reanalyses of historical data. Ultimately, we urgently need a deeper understanding of the relationships between patterns and processes in greening and browning dynamics to improve estimates of the globally significant climate-change feedbacks in high-latitude ecosystems[20].

Data availability

Data come from publicly available remote sensing and ecological datasets including: MODIS (https://modis.gsfc.nasa.gov/), GIMMS3g.v1 (https://nex.nasa.gov/nex/projects/1349/), the High Latitude Drone Ecology Network (https://arcticdrones.org/), shrub abundance, annual growth ring and phenology datasets (https://github.com/ShrubHub/QikiqtarukHub, https://arcticdata.io/catalog/view/doi:10.18739/A24X0Q, https://arcticdata.io/catalog/view/doi:10.18739/A28Q18, https://arcticdata.io/catalog/view/doi:10.5065/D6542KRH).

Code availability

Code is available in a GitHub repository (https://github.com/ShrubHub/GreeningHub).

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Author contributions

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