

Complexity revealed in the greening of the Arctic

Reference

Myers-Smith, I.H., Kerby, J.T., Phoenix, G.K. *et al.* Complexity revealed in the greening of the Arctic. *Nat. Clim. Chang.* **10**, 106–117 (2020). <https://doi.org/10.1038/s41558-019-0688-1>

Weblink

<https://www.nature.com/articles/s41558-019-0688-1>

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85 **Editor's Summary**

86 As tundra ecosystems respond to rapid Arctic warming, satellites records suggest a widespread
87 greening. This Perspective highlights the challenges of interpreting complex Arctic greening trends
88 and provides direction for future research by combining ecological and remote sensing approaches.

89

90 **Abstract**

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

100

101 **Main text**

102 The Arctic has warmed at more than twice the rate of the rest of the planet in recent decades^{1,2}. Over
103 the past forty years, satellite-derived vegetation indices have indicated widespread change at high
104 latitudes³⁻¹⁶. Satellite records allow for the quantification of change in places that are otherwise
105 unevenly sampled by *in-situ* ecological observations¹⁷. Positive trends in satellite-derived vegetation
106 indices (often termed Arctic greening)¹⁵ are generally interpreted as signs of *in-situ* increases in
107 vegetation height, biomass, cover and abundance^{5,18,19} associated with warming^{5,14}. In the most
108 recent Intergovernmental Panel on Climate Change report, tundra vegetation change including
109 greening trends derived from satellite records²⁰ was identified as one of the clearest examples of the
110 terrestrial impacts of climate change. Large-scale vegetation-climate feedbacks at high latitudes
111 associated with greening could alter global soil carbon storage and the surface energy budget^{21,22}.
112 In recent years, slowing or reversal of apparent greening from satellite studies have been reported
113 in some regions (sometimes termed Arctic browning)^{3,4,12,13,15,23,24}. This slowdown is seemingly at

114 odds with earlier responses to long-term warming trends^{3,25}. Research now indicates substantial
115 heterogeneity in vegetation responses to climate change in the Arctic^{18,19,26,27}. However, the
116 mechanistic links between satellite records and *in-situ* observations^{3,6,24} remain unclear due to
117 conceptual and technical barriers in their analysis and combined interpretation.

118

119 **A review of Arctic greening**

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

132

133 *Vegetation indices as proxies of vegetation productivity*

134 Long-term trends in global vegetation dynamics are most commonly quantified from time series of
135 spectral vegetation indices derived from optical satellite imagery (Figure 1). These indices are
136 designed to isolate signals of leaf area and green vegetation cover from background variation by
137 emphasizing reflectance signatures in discrete regions of the radiometric spectrum^{6,29–32}. Common
138 vegetation indices include the Normalized Difference Vegetation Index (NDVI, Figure 2), Enhanced
139 Vegetation Index (EVI) and Soil Adjusted Vegetation Index (SAVI), among others^{33–35}. NDVI
140 correlates with biophysical vegetation properties like Leaf Area Index (LAI) and the fraction of
141 Absorbed Photosynthetically Active Radiation (fAPAR)^{14,36–39}. However, these vegetation indices
142 were not developed in polar contexts⁴⁰ and are only proxies of photosynthetic activity rather than

143 direct measurements of biological productivity^{33,39,41}. NDVI is the most commonly used vegetation
144 index because it is simple to calculate with spectral bands monitored since the launch of early-
145 generation Earth-observing satellites in the 1970s (Figure 2) and is perhaps best defined as a
146 measure of above-ground vegetation greenness.

147

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

159

160 *Ecological factors influencing greening and browning trends*

161 The ecological processes underlying spectral greening or browning measured by satellites are
162 diverse and may unfold across overlapping scales, extents and timeframes. In tundra ecosystems,
163 vegetation changes linked to spectral greening could include: encroachment of vegetation on
164 previously non-vegetated land surfaces^{18,47}, changes in community composition – such as tundra
165 shrub expansion^{5,19,27}, and/or changes in plant traits such as height^{48,49}, leaf area, or phenology^{50–52}.
166 Tall shrub tundra typically has a higher NDVI than other tundra plant types^{49,53,54}, and bare ground²⁹
167 has a much lower NDVI than vegetated tundra (Figure 2). Spectral browning could be related to a
168 variety of factors including for example loss of photosynthetic foliage¹² or increases in bare ground
169 cover due to permafrost thaw⁵⁵ (Figure 1). Thus, changes in the species composition, growth form
170 and traits of plant communities can influence greening and browning trends.

171

172 *Physical factors influencing greening and browning trends*

173 Widespread non-biological changes in high-latitude ecosystems could confound and decouple
174 spectral greening or browning trends from changes in plant productivity (Table 1). Land cover,
175 topography, and associated soil moisture, surface water, land-surface disturbances and snow-melt
176 dynamics can all influence the measured spectral greenness of landscapes^{56–63} and likely influence
177 greening trends. For example, changes in the extent of summer snow patches⁶³, surface water⁶⁰ or
178 surface soil moisture⁵⁹ that are often associated with landscape-scale topographic variation could
179 influence the measured NDVI of the land surface. At high latitudes, optical satellite sensors are only
180 effective for a short annual window due to the prolonged polar night, while low sun angles and
181 persistent cloud cover reduce data quality in the summer season (Table 1). The unique physical
182 properties of high-latitude ecosystems in addition to the constraints of polar remote sensing are often
183 underemphasized in remote sensing studies of Arctic vegetation change.

184

185 *Arctic browning and heterogeneity of spectral greening trends*

186 Not all areas of the Arctic are spectrally greening (Figure 1), and in recent years spectral browning
187 and heterogeneity of spectral greening trends have been highlighted^{3,4,12,13,23}. Ecological
188 explanations for vegetation browning include for example the sudden loss of photosynthetically
189 active foliage due to extreme climatic events^{64–67}, biological interactions (e.g., disease or herbivore
190 outbreaks)^{68–70}, permafrost degradation^{23,55} (Figure 1), increases in standing dead biomass⁷¹, coastal
191 erosion⁷², salt inundation⁷³, altered surface water hydrology^{74,75} or fire^{9,76,77}. Spectral browning,
192 however, could be attributed to reduced productivity caused by adverse changes in growing
193 conditions such as lower water availability, shorter growing seasons³ or nutrient limitation²⁷.
194 Nonetheless, long-term spectral greening trends remain far more pervasive than spectral browning
195 in tundra ecosystems. Figures vary from 42% greening and 2.5% browning from 1982 to 2014 in the
196 GIMMS3g AVHRR dataset⁷⁸, 20% greening and 4% browning from 2000 to 2016 in Landsat data¹⁵
197 and estimates of 13% greening and 1% browning for the MODIS trends calculated for 1000 random
198 points in the tundra polygon in Figure 1 from 2000 to 2018. At circumarctic scales, the magnitude,
199 spatial variability, and proximal drivers of patterns and trends of spectral greening versus browning
200 are not well understood.

201

202 *Correspondence between satellite and ground-based observations*

203 Evidence for correspondence among *in-situ* vegetation change and trends in satellite-derived
204 vegetation indices is mixed^{47,79–81}. NDVI trends across satellite datasets do not necessarily directly
205 correspond with one another^{6,9}, nor does any one sensor or vegetation index combination
206 correspond directly with *in-situ* vegetation change⁴⁷. For example, NDVI has been related to
207 interannual variation in radial shrub growth^{5,10,82}, yet how radial growth links to change in leaf area,
208 aboveground biomass, or landscape measures of productivity is not always clear^{83–85} (Figure 3).
209 AVHRR NDVI greening trends did not correspond with the lack of change observed with Landsat
210 NDVI data and *in-situ* plant composition between 1984 and 2009 in North Eastern Alaska⁴⁷. Direct
211 comparisons of productivity changes from vegetation cover estimates^{18,86}, biomass harvests⁵³ or
212 shrub growth⁸⁷ are complicated by the lack of annual-resolution *in-situ* data and low sampling
213 replication across the landscape. We attribute the mixed evidence for correspondence between *in-*

214 *situ* and satellite-derived measures of tundra vegetation change and greening to the complexities of
215 existing terminology, challenges of interpretation of spectral vegetation indices at high latitudes, and
216 the scaling issues as outlined below.

217

218 In addition to productivity analyses, changes in growing season length and advances in plant
219 phenology have been documented using both satellite^{43,78,88–91} and ground-based datasets, and here
220 also paired comparisons do not always correspond (Figure 4). Measures of longer growing seasons
221 have been attributed to earlier snowmelt and/or earlier leaf emergence in spring⁹², and longer periods
222 of photosynthetic activity or later snowfall in autumn⁹³. However, few studies have monitored both
223 leaf emergence and senescence of tundra plants *in situ* and so far provide no evidence for an
224 increasing growing period at specific sites^{94,95}. In addition, community-level analyses indicate shorter
225 flowering season lengths around the tundra biome⁵⁰. Shifts in plant phenology with warming⁵⁰ could
226 also be linked to changing species composition or diversity^{18,48,86}, thus influencing the phenological
227 diversity across the landscape^{96,97}. Satellite records may not capture the ecological dynamics of
228 vegetation phenology at high latitudes, as snow cover can obscure the plant seasonal signal and
229 deciduous plants only make up a portion of the vegetated land cover. Thus, uncertainty remains
230 whether satellite-derived changes in circumarctic phenology represent a longer snow-free period
231 uncoupled from the vegetation response or an actual realized longer growing season of plants^{94,98–}
232 ¹⁰⁰.

233

234 **Clarifying the terminology**

235 To distinguish spectral greening and browning events from longer-term trends, we propose clarified
236 definitions of events and trends. For an individual pixel, we define the *spectral trend* as an increase
237 or decrease in NDVI (or other spectral vegetation index) over decadal time scales and a *spectral*
238 *event* as a temporal outlier in the vegetation index relative to the long-term trend. Trends should be
239 determined using a Theil-Sen estimator or similar robust statistical test for analyses of satellite
240 data^{30,101}. We define a *spectral greening trend* as an increase of the vegetation index over decadal
241 time scales. *In situ*, we interpret a *vegetation greening trend* as improved conditions for
242 photosynthesis, reduced resource limitation and/or positive responses to disturbance in plant

243 communities, resulting in greater aboveground biomass, leaf area, productivity or changes in plant
244 community composition. We define a *spectral browning trend* as a decrease in the vegetation index
245 over decadal time scales. A *vegetation browning trend* may correspond with an *in-situ* change in
246 vegetation productivity due to plant dieback or loss of vegetation cover through biotic or abiotic
247 disturbances. We define *spectral greening events* as short-term increases in vegetation index
248 greenness that can be attributed to an ecological process such as revegetation of ground cover after
249 fire and *spectral browning events* as short-term decreases in the vegetation index that can be
250 attributed to a disturbance such as permafrost thaw or plant dieback. The definitions we propose
251 here distinguish between slower acting climatic or biotic drivers of greening or browning trends
252 versus event-driven changes caused by weather, biotic pulses, or other regional events such as fire.
253

254 *Differentiating events and trends*

255 In any measure of remotely sensed or field-based greening separate consideration of trends and
256 events will increase ecological interpretability (Figure 5). Spectral greening and browning trends
257 operate at any spatial scale, from localised patches to landscapes or even biome extents over
258 decades. In contrast, spectral greening and browning events, such as those caused by vegetation
259 dieback or rapid vegetation increase after disturbance, are often restricted to patch and regional
260 scales over shorter durations. Events often have more limited extents relative to trends due to their
261 proximal causes, like changes in herbivory or precipitation. Broader scale events are also possible
262 (e.g. globally synchronized reductions in vegetation productivity caused by changes in insolation
263 related to an intense volcanic eruption¹⁰²). Therefore, greening or browning events might be
264 embedded within overall spectral greening or browning trends, both temporally and/or spatially,
265 without necessarily driving them (Figure 5). Examining the trend direction, magnitude and variance
266 around the fit over time can shape more detailed investigations into the ecological interpretation of
267 Arctic spectral greening trends.

268

269 *The influence of baselines and temporal sampling*

270 The baseline to which we compare productivity change will influence our interpretation of trends¹⁰³.
271 Spectral greening or browning trends and events may result in threshold changes where on-the-

272 ground productivity does not return to the longer-term baseline (Figure 5; e.g., pulse in recruitment
273 at treeline¹⁰⁴ or shrubline¹⁰⁵ or a large fire⁷⁷). In both satellite datasets and field observations, the
274 baseline conditions are often constrained by the limitations of data availability rather than any
275 deliberately selected starting point⁶. The low temporal sampling frequency of a few days to a few
276 weeks of many legacy remote-sensing datasets (e.g., AVHRR, MODIS, Landsat, etc.) also
277 introduces temporal scale-dependent effects that may be magnified in Arctic systems (Table 1). For
278 example, comparisons of phenology across latitudes can be less reliable at higher versus lower
279 latitudes due to shorter growing seasons and therefore fewer satellite data collection points for use
280 in change detection analyses^{42,88,89}. Metrics based on the annual maximum NDVI of a given pixel
281 are more likely to be influenced by temporal sampling artefacts at high latitudes than those that
282 integrate productivity estimates through time, such as the growing season integrated NDVI
283 (GSINDVI)⁴², time-integrated NDVI (TiNDVI)⁴³ or early growing season integrated NDVI indices⁴⁴.
284 Trends in either instance could be observed or not observed due to statistical reasons related to
285 sample size and/or the strength or linearity of the trend. Thus, simple linear analyses of annual
286 greenness metrics derived from satellite data may not always capture real-world ecological change
287 (Figure 5).

288

289 **Challenges in the interpretation of vegetation indices**

290 In addition to the need for more clearly defined terms, challenges remain in the ecologically
291 meaningful interpretation of long-term trends in optical satellite data, especially at high latitudes. The
292 statistical relationship between a vegetation index and biomass, leaf area, phenology, or any other
293 measures of productivity can vary due to a suite of intrinsic (e.g., sensor design, quality flagging
294 algorithms), extrinsic (e.g., atmospheric conditions, sun angle, snow cover)^{6,106} and biological
295 factors¹⁰⁷ (Table 1). For example, the centre wavelength and width of spectral bands (e.g., in the red
296 or near-infrared) used to generate vegetation indices were designed for different purposes in
297 different sensors (Figure 2). While the NDVI formula may be the same, the covered spectral
298 wavelength ranges differ between different datasets¹⁰⁸ (Figure 2b). Thus, the datasets may be more
299 or less sensitive to specific non-vegetative influences, such as atmospheric scattering or the
300 magnitude of spectral mixing associated with non-vegetated surfaces⁵⁷. Spectral unmixing is the
301 process of decomposing the spectral signature of a mixed pixel into the abundances of a set of
302 endmember categories¹⁰⁹. Longer-term vegetation change is difficult to resolve from cross-sensor
303 comparisons among different satellite datasets or even among intercalibrations of the same sensor
304 type (Figure 1). For these reasons, caution is warranted when comparing vegetation indices derived
305 from different satellite products or even versions of the same product with different atmospheric
306 corrections, quality assessments, and spatial/temporal compositing approaches^{6,108}. Differences in
307 NDVI signal processing are actively studied by the remote-sensing community (Table 1), but could
308 be better accounted for or quantified in Arctic greening studies.

309

310 *Nonlinearities in NDVI as a vegetation proxy*

311 Direct interpretations of vegetation changes from spectral data are contingent on the local
312 relationship between NDVI and *in-situ* vegetation. The statistical relationships between vegetation
313 indices and measures of Arctic vegetation biomass are nonlinear^{29,110} (Figure 2). This nonlinearity
314 presents challenges for trend interpretation that are illustrated in Figure 2a. Here, an absolute
315 increase in biomass for a 'low biomass' community towards a 'moderate biomass' community would
316 result in a positive NDVI trend, but that same absolute biomass increase from moderate to high
317 biomass would show virtually no trend in NDVI due to saturation (Figure 2). Thus, the relationship to

318 common ecological variables like changes in biomass or shrub ring widths (Figure 4) can be
319 obscured by nonlinearities. Because the greening and browning terms are tied to changes in
320 vegetation proxies, rather than direct biological measures, a lack of correspondence could occur
321 between remotely-sensed vegetation proxies and *in-situ* vegetation change (Figure 2, 4 and 5). Such
322 potential discrepancies exemplify why caution should be used when interpreting linear trends in
323 proxies like NDVI (Figure 1) that are nonlinearly related to vegetation productivity without the use of
324 *in-situ* data to corroborate conclusions.

325

326 *Scaling issues in Arctic greening analyses*

327 Scale and hierarchies present a longstanding challenge in the interpretation of remotely-sensed
328 vegetation proxies^{111–113} (Figure 5). All long-term vegetation proxy time series (Landsat, MODIS,
329 AVHRR) spatially aggregate spectral data to pixels (i.e., grains) that span hundreds of square metres
330 to tens of square kilometres. The spectral signatures of plants and non-vegetative features in a
331 landscape are reduced to a single value. The loss of variability within pixels masks information useful
332 for the attribution of greening signals to processes across ecological hierarchies from populations
333 and communities to ecosystems (Table 1, Figure 3 and 5). For example, within a single AVHRR
334 GIMMS3g pixel, a subselection of 1 x 1 km pixels are upscaled to 8 x 8 km³². Within this aggregated
335 pixel, ecological contributions to spectral greening signals such as increased shrub cover on south-
336 facing slopes or revegetation of drained lake beds may be mixed with browning signals from for
337 example disturbances such as retrogressive thaw slumps or vegetation trampling by herbivores
338 (Figure 1). High-latitude pixels may also contain shadows caused by low-sun angle, patchy snow-
339 and/or cloud-cover (Table 1). Thus, the emergent time series from such a pixel describes no single
340 vegetation dynamic or environmental factor, but rather their integrated spectral responses. Broad-
341 scale patterns of spatial variability in greening and browning across pixels are also influenced by
342 grain size¹¹³ (Figure 1, 2, 5). Finer resolution satellites such as Landsat can reduce, but not
343 necessarily eliminate such spectral mixing¹⁵. However, the extent to which the sometimes-
344 contradictory greening and browning signals found across different spectral datasets can be
345 attributed to the influence of the scale of measurement is poorly understood.

346

347 *Complexities of capturing phenology*

348 Measuring landscape phenology with satellite data presents additional challenges to ecological
349 interpretation of Arctic greening (Table 1). The variability of timing of satellite imagery from year to
350 year particularly at high latitudes⁹¹ can confound measures of phenology (known as phenometrics).
351 Cloud or fog cover is highly variable and sensitive to changing sea ice conditions in coastal Arctic
352 sites⁴⁴. Seasonal variation in cloud and fog cover influences both data availability and image
353 compositing approaches in many phenology products⁹¹. In addition, vegetation metrics from early
354 spring are much more likely to be influenced by snow, standing water or low sun angle than those
355 closer to peak biomass in mid- to late-summer^{8,54,59}. However, early spring is a critical period for
356 establishing a baseline for curve fitting or thresholding used to derive phenometrics. Ultimately no
357 phenometric is best suited to all Arctic environments or time periods¹¹⁴. Snow regimes and land cover
358 variability differ annually and regionally and thus phenometrics using coarse-grain imagery integrate
359 different abiotic and biotic signals at different points in space and time¹¹⁴. Phenological differences
360 of days to weeks or even months can result from analyses using different methods and metrics for
361 the same datasets at the same location¹¹⁵. These relative differences are of substantial ecological
362 importance given the short growing seasons of the Arctic^{78,114} (Figure 4). Circumarctic analyses of
363 vegetation indices generally indicate that phenological shifts in the spectral greenness of the land
364 surface are widespread^{78,88–90}. However, the magnitude and extent of spatial and temporal scaling
365 issues in high-latitude remotely-sensed phenology trends warrant further consideration and
366 research¹¹².

367

368 ***Towards a consensus perspective on Arctic greening***

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

374

375 1. *Addressing scale issues by integrating proximal remote sensing and in-situ observations into*
376 *circumarctic greening analyses*

377 Analyses of observations across scales will allow us to bridge the gap and improve our mechanistic
378 understanding of the links between *in-situ* vegetation dynamics and broader remotely-sensed
379 patterns and trends. New instruments for carrying out *in-situ* and proximal remote-sensing
380 observations for comparison with satellite data are developing rapidly. However, we must urgently
381 develop standardized field data collection protocols. In order to facilitate future synthesis, we need
382 to incorporate data from long-term ecological monitoring^{12,18,86,94}, historical imagery¹¹⁶, phenocam
383 networks¹¹⁷, flux towers¹¹⁸, high-resolution imagery such as from aircraft, towers, and drones¹¹⁹ and
384 satellites.

385

386 2. *Incorporation of heterogeneity and uncertainty into analyses to improve confidence in*
387 *detection of Arctic greening trends*

388 New finer spatial or temporal resolution data will inform analyses of historic greening trends. Current
389 circumarctic Landsat analyses are shedding light on greening trends by exploiting finer spatial
390 resolution data while accounting for the lower temporal resolution of observation records¹⁵. Recent
391 and ongoing release of finer-resolution satellite datasets (e.g., EU-funded Sentinel missions, Digital
392 Globe, Planet constellations) and data products (e.g., the Arctic Digital Elevation Model) will provide
393 finer spatial (2-10 m) and/or temporal resolution (1-5 days) data across the Arctic¹²⁰. We can gain a
394 better understanding of past spectral greening signals from legacy satellite datasets by conducting
395 standardized reprocessing with for example statistical methods incorporating uncertainty in
396 observations such as image quality information, improved atmospheric corrections and snow
397 detection.

398

399 3. *Inclusion of new observational tools beyond optical vegetation indices to clarify the*
400 *mechanistic links between spectral greening and vegetation change*

401 In addition to incorporating finer resolution datasets, new types of data collection can inform our
402 understanding of what greening patterns and trends represent. Emerging remote sensing campaigns
403 using hyperspectral sensors or those that can measure Solar-Induced Fluorescence (SIF)¹²¹ will

404 provide new insights into vegetation dynamics. However, future sensor development across satellite,
405 aircraft and near-surface platforms should be designed to maximize comparability. In addition to new
406 data collection, novel data integration approaches, for example those employing machine learning,
407 will provide greater insights into biome-scale analyses linking remote sensing observations with
408 ecological change in high-latitude ecosystems^{21,122}.

409

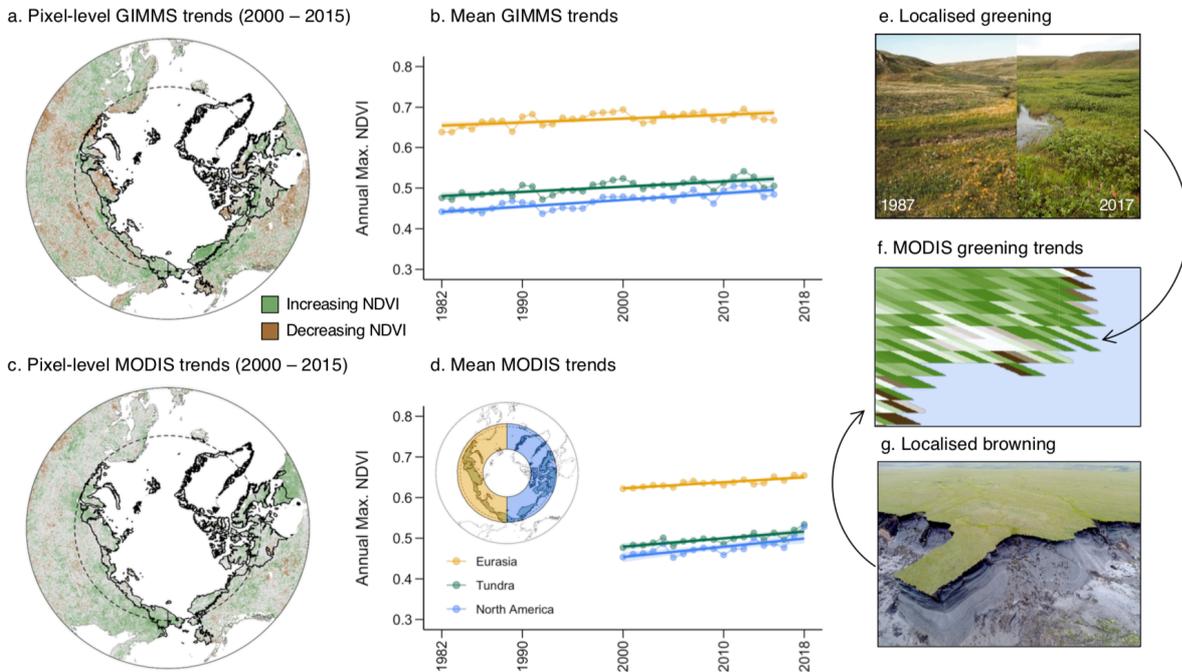
410 **Conclusions**

411 Recent research has highlighted the complexity in observed Arctic greening and browning trends.
412 Although satellite data have been used to detect and attribute global change impacts and resulting
413 climate feedbacks in Arctic ecosystems^{20,22}, numerous questions and uncertainties remain. The
414 three major challenges in resolving these uncertainties are: 1) improving the clarity of the definitions
415 of widely used terminology associated with greening and browning phenomena, 2) promoting the
416 understanding of the strengths and limitations of vegetation indices when making ecological
417 interpretations and, 3) better incorporating and accounting for different scales of observation and
418 uncertainty in analyses of changing tundra productivity and phenology. New sensors and better
419 access to legacy data are improving our ability to remotely sense vegetation change. However, new
420 data alone will not provide solutions to many of the longstanding conceptual and technical
421 challenges. The complexity of Arctic greening will only be fully understood through multidisciplinary
422 efforts spanning the fields of ecology, remote sensing, earth system science and computer science.
423 As a field, we need to look forwards to quantify contemporary and future change, but also backwards
424 by conducting reanalyses of historical data. Ultimately, we urgently need a deeper understanding of
425 the relationships between patterns and processes in greening and browning dynamics to improve
426 estimates of the globally-significant climate change feedbacks in high-latitude ecosystems²⁰.

427 Table 1. A variety of geophysical^{13,106,123}, environmental^{44,60,61} and ecological^{12,47,49,54,57,110} factors can
 428 influence the magnitude and direction of change in vegetation indices and are particularly
 429 problematic at high latitudes⁶. The effects include: 1) Radiometric effects: differences among satellite
 430 datasets including band widths, atmospheric effects, cloud-screening algorithms, sensor
 431 degradation, orbital shift and bidirectional reflectance distribution functions originating from
 432 differences in field of view and sun geometries. 2) Spectral mixing: the blending of sub-pixel spatial
 433 heterogeneity that can influence the overall pixel signal (Figure 2). 3) Adjacency effects: the
 434 reflectance of surrounding pixels that can influence the signal of a given pixel (Figure 2). And, 4) a
 435 variety of environmental and ecological factors from snow melt and soil moisture dynamics to
 436 composition of evergreen versus deciduous or vascular versus non-vascular plants.

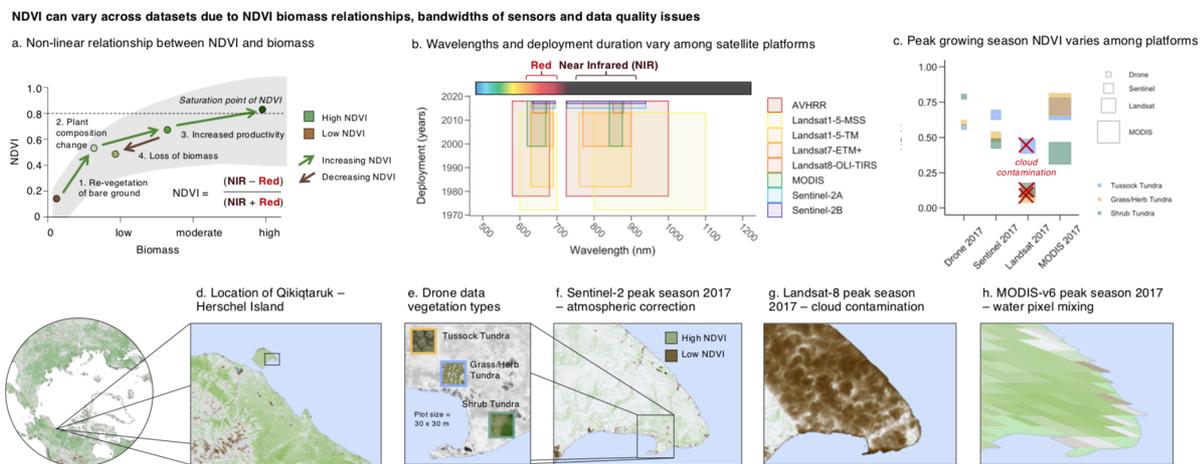
Factors influencing vegetation indices	Specific effects	Influence on apparent greening patterns and trends
Low sun angle	Radiometric effects	At high latitudes, low sun angles and cloud shadows can have a greater influence on vegetation indices relative to lower latitudes ⁶² . NDVI varies with sun angle, 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 due 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, however 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 sub-nivean phenological progression and/or may overemphasise 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 covary with vegetation change ¹²⁵ . Furthermore, NDVI is relatively insensitive to changes in very sparsely vegetated (e.g., the High Arctic ¹²⁷) and very densely vegetated (e.g., 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. Growing season length decreases at higher latitudes, thus the impact of missing data is of a greater magnitude as latitude increases.
Rapid plant phenology	Chosen phenometric	The specific metrics used to quantify phenology will influence the resulting patterns observed ⁹¹ . Combining datasets with different spatial and temporal resolutions can limit comparisons (Figure 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 geographic 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} (Figure 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, etc. 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} .

Satellite records indicate greening trends across the circumpolar Arctic

438

439 **Figure 1. Arctic greening, which varies across space and time and among satellite datasets,**
 440 **is driven by both actual in-situ change and, in part, by the challenges of satellite data**
 441 **interpretation and integration.** Trends in maximum NDVI vary spatiotemporally and the magnitude
 442 of changes is different depending on what satellite imagery is analysed (a and c, data subsetted to
 443 temporally overlapping years; b and d, GIMMS3gv1 1982 to 2015 and MODIS MOD13A1v6 2000 to
 444 2018). Regional trends may summarise localised greening, for example shrub encroachment (e) and
 445 browning such as permafrost thaw (g) occurring at the pixel scale on Qikiqtaruk - Herschel Island in
 446 the Canadian Arctic (f). NDVI trends (a and c) were calculated using robust regression (Theil-Sen
 447 estimator) in the Google Earth Engine¹²⁹. Dashed line indicates the Arctic Circle and the black
 448 outlined polygon (a and c) and green 'Tundra' line (b and d) indicates the Arctic tundra region from
 449 the Circumpolar Arctic Vegetation Map (www.geobotany.uaf.edu/cavm/). The inset map in d
 450 indicates the regions for the mean trends for yellow 'Eurasia' and blue 'North America' polygons.



451

452 **Figure 2. Ecological interpretation of trends in the Normalized Difference Vegetation Index**453 **(NDVI) requires a consideration of non-ecological factors.** NDVI, calculated as the difference

454 between red and near infrared bands (NIR), has a non-linear relationship with several common

455 metrics of plant productivity, like biomass and LAI (a). Satellite platforms have different spectral band

456 widths which can influence calculations of NDVI despite shared centre wavelengths (b). NDVI values

457 from commonly available satellite data products and drone datasets (c) differed substantially across

458 products and across plots of three different vegetation types (e) during the period of peak biomass

459 in 2017 on Qikiqtaruk – Herschel Island, Yukon. Here, factors such as a lack of atmospheric

460 correction (f), cloud or fog contamination (g), sub-pixel mixing (h), different plot grain sizes of data in

461 more or less heterogeneous vegetation cover and timing of data acquisition could have all influenced

462 NDVI values. Data were analysed and extracted for 30 x 30 m plots from 13th July to 4th August in463 2017 using the Google Earth Engine¹²⁹ for the MODIS MYD13A1v6 (pixel size = 500 m x 500 m)

464 and Landsat 8 (pixel size = 30 m x 30 m) NDVI product, and the top-of-atmosphere Sentinel-2 NDVI

465 product without atmospheric corrections (pixel size = 10 m x 10 m) NDVI, and Pix4D-processed

466 drone data collected using a radiometrically calibrated four-band multispectral sensor (Sequoia, pixel

467 size = 12 cm x 12 cm) on an FX-61 fixed-wing platform with the High-latitude Drone Ecology Network

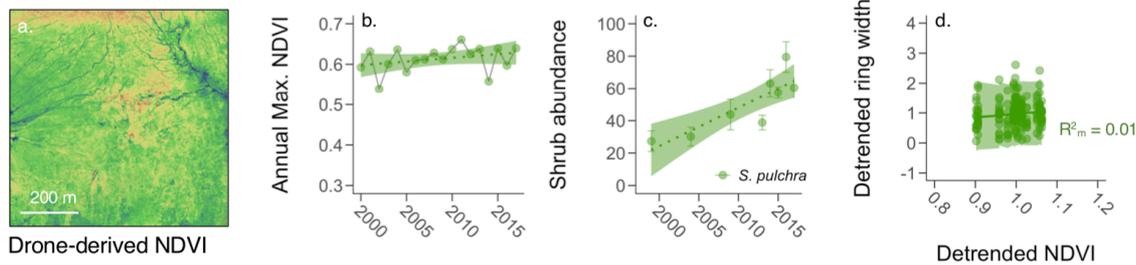
468 protocols (<https://arcticdrones.org/>). We purposefully present data with quality and processing issues

469 above to highlight the challenges in quantifying NDVI in regional-to-global studies where data quality

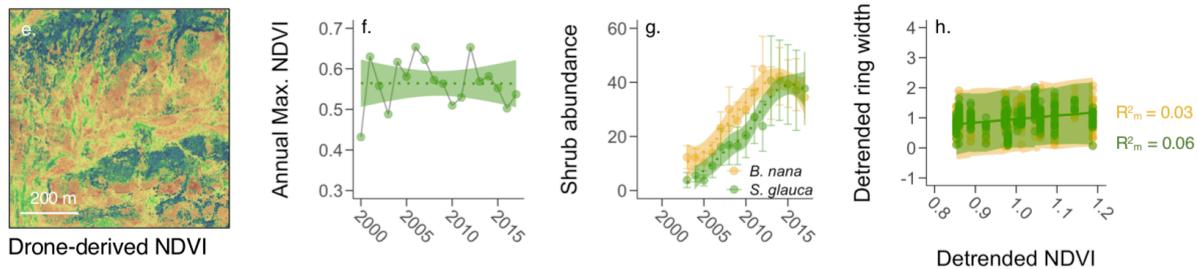
470 issues may be spatially or temporally variable among locations.

Spatial heterogeneity in landcover can influence NDVI ~ vegetation relationships

Qikiqtaruk, Canada – low landscape-level heterogeneity and increasing shrub abundance and variable radial growth



Kangerlussuaq, Greenland - high landscape-level heterogeneity, increased yet stabilized shrub abundance and variable radial growth

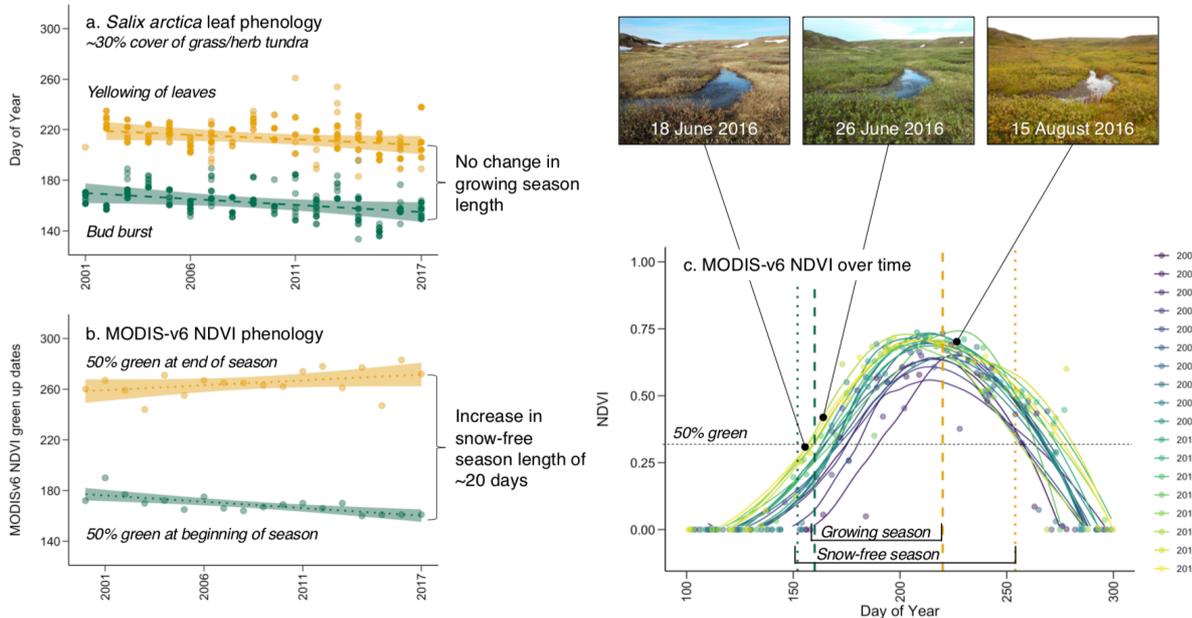


471

472 **Figure 3. Sub-pixel spatial heterogeneity in vegetative greening and browning cannot be**
 473 **accurately captured at coarser grains.** Landscape patterns (a, e), trends (b, f), and variability (d,
 474 h) in NDVI may not represent *in-situ* observations of vegetation change. NDVI trends and interannual
 475 variability had mixed correspondence with increases in shrub abundance (c, g) and interannual
 476 variability in shrub growth on Qikiqtaruk – Herschel Island, Yukon⁹⁴ (c, point framing in twelve 1-m²
 477 plots; d, *Salix pulchra* = 21, <https://github.com/ShrubHub/QikiqtarukHub>) and Kangerlussuaq,
 478 Greenland^{84,130} (g, 13 0.25-m² plots; H, *Betula nana* = 42, *Salix glauca* = 32,
 479 <https://arcticdata.io/catalog/view/doi:10.18739/A24X0Q>,
 480 <https://arcticdata.io/catalog/view/doi:10.18739/A28Q18>,
 481 <https://arcticdata.io/catalog/view/doi:10.5065/D6542KRH>). Errors are standard error bars around
 482 mean values (c, g) and 95% credible intervals for a Bayesian hierarchical model of the relationship
 483 between detrended annual growth rings and NDVI with shrub individual and year as random effects
 484 (d, h). Detrending was done using a spline fit from the *dpIR* package in R. Credible intervals for
 485 model slopes overlapped with zero (d, h). Marginal R² values indicate the variance in detrended ring
 486 widths explained by detrended NDVI (d, h). Landscape NDVI patterns (a and e) were measured
 487 using a Parrot Sequoia and FX-61 fixed wing platform according to High-latitude Drone Ecology
 488 Network protocols in the summer of 2017 (<https://arcticdrones.org/>) and analysed using the Pix4D

489 software. Coarser-grain NDVI time series (MODIS MOD13A1v6, 500m pixels) were calculated using
490 Google Earth Engine¹²⁹ and the Phenex package in R.

Plant phenology does not always match land-surface greenness across the growing season



491

492 **Figure 4. Satellite-derived phenology estimates do not always match with in-situ plant**493 **phenology observations.** Satellite-observed snow-free season length of the land surface (here

494 defined as the period with NDVI greater than 50% of the max NDVI, b and c) might not directly

495 correspond to the growing season of vascular plants in tundra ecosystems, particularly in autumn

496 (a). Snow-melt dynamics can obscure the plant phenology signal and non-vascular or evergreen

497 plants can obscure the deciduous vascular plant seasonal signal. Plant phenology data were

498 collected at 20 monitoring plots on Qikiqtaruk-Herschel Island for the species *Salix arctica*, which

499 makes up approximately 30% of the cover in the grass- and forb-dominated vegetation type.

500 Analyses indicate that both leaf emergence and senescence have become earlier, resulting in no

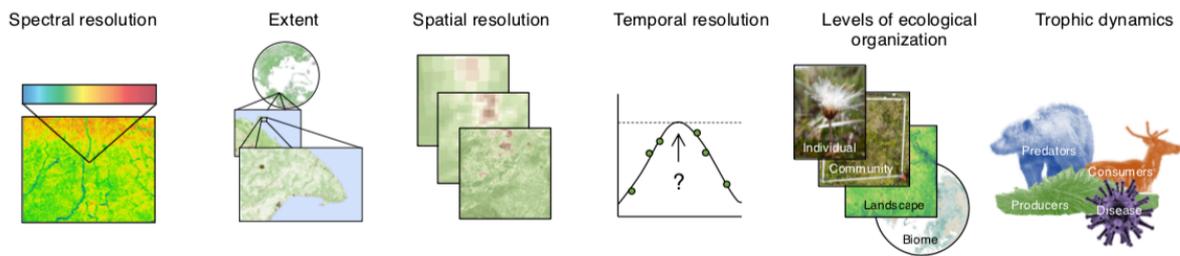
501 change in realized growing season length despite substantial increases in the snow-free period of

502 the land surface⁹⁴ (a – c, <https://github.com/ShrubHub/QikiqtarukHub>). Satellite data are MODIS503 MOD13A1v6 extracted for the pixel containing the phenology transects using Google Earth Engine¹²⁹

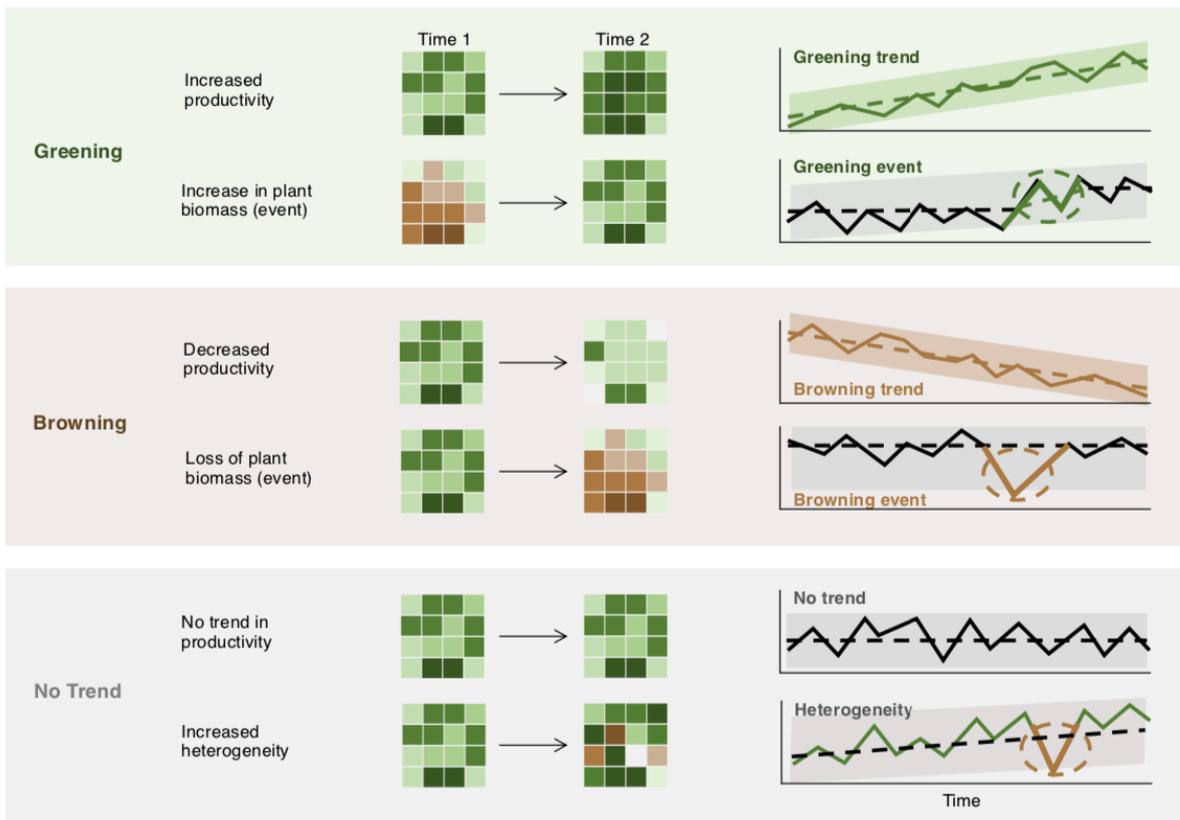
504 and the Phenex package in R (b and c).

Greening and browning complexity can be addressed by incorporating scale and clarifying ambiguity in terminology

a. Arctic greening patterns and trends are influenced by issues of scale



b. Spatial heterogeneity in NDVI greening/browning patterns can influence greening/browning trends over time



505

506 **Figure 5. Arctic greening is influenced by both issues of measurement scale and inference**
 507 **across ecological hierarchies.** Spectral resolution (Figure 2), extent (Figure 1), spatial resolution
 508 (Figure 2), landscape-level heterogeneity (Figure 3), temporal resolution (Figure 4), and ecological
 509 factors all influence the interpretation of greening trends (a). Within-pixel changes in land surface
 510 greening and browning events and trends can translate into different greening and browning patterns
 511 as their effects are scaled up (b). Ecological processes that comprise greening and browning trends
 512 include a combination of events, such as a pulse of plant recruitment or growth, a dieback of plants
 513 due to an extreme winter climate event, herbivore or disease outbreak or other disturbance and
 514 subsequent recovery. Longer-term change such as increasing shrub cover or progression of
 515 permafrost disturbances can also influence real-world NDVI time series. These different factors add

516 complexity to the interpretation of Arctic greening trends. The scale and hierarchy of observations
517 need to be incorporated into and/or accounted for in future analyses of Arctic greening.

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521

522 **Author Contributions**

523 IHM-S and JTK conducted the analyses and wrote the manuscript with contributions from all authors.
524 GKP, JWB and HE contributed substantially to early versions of the manuscript. IHM-S, JTK, JJA,
525 AMC, CJ, SA-B, HJDT and ESP collected drone and *in-situ* data. This paper results from two
526 collaborations: the sTundra working group at the German Centre for Integrative Biodiversity
527 Research (iDiv) led by IHM-S, SCE and ADB and the 'Event Drivers of Arctic Browning Workshop'
528 at the University of Sheffield led by GKP.

529

530 **Funding**

531 Data collection on Qikiqtaruk-Herschel Island was funded by the UK Natural Environment Research
532 Council (NERC) NE/M016323/1 [to IMS] and a National Geographic Society grant CP-061R-17 and
533 a Parrot Climate Innovation Grant [to JTK]. Data collection at Kangerlussuaq, Greenland was
534 supported by the US National Science Foundation (NSF) grants 0724711, 0713994, 0732168,
535 0902125, 1107381, 1525636, 1748052 and the National Geographic Society [to EP], as well as an
536 Arctic Institute of North America Grant-in-Aid [to CJ]. The sTundra working group was supported by
537 sDiv, the Synthesis Centre of the German Centre for Integrative Biodiversity Research (iDiv) Halle-
538 Jena-Leipzig (DFG FZT 118). The Event Drivers of Arctic Browning workshop was funded by P3-
539 Plant Production and Protection (<http://p3.sheffield.ac.uk/>). Several members of the team are
540 supported by the NASA ABoVE program (<https://above.nasa.gov/>). Additional funding was provided
541 by the Research Council of Norway grant 287402 [to JWB and HT] and 294948 [to FS, JWB, AB,
542 HT, and FJWP], the NERC doctoral training partnership grant NE/L002558/1 [to JJA and HJDT], the
543 US NSF grants PLR-1504134, AGS 15-02150, PLR16-03473 [to LAH], the Natural Sciences and
544 Engineering Research Council of Canada and the Canadian Centennial Scholarship Fund [to SAB],
545 the Academy of Finland decision 256991 and JPI Climate 291581 [to BCF], the NASA ABoVE grants
546 NNX17AE44G and NNX17AE13G [to SJG & LTB], NSF grants PLR-0632263, PLR-0856516, PLR-

547 1432277, PLR-1504224, PLR-1836839 [to RDH], the US NSF grant PLR-1417745 [to MML], an
548 NERC IRF NE/L011859/1 [to MMF], Independent Research Fund Denmark 7027-00133B and Villum
549 Fonden VKR023456 to [SN], the Norwegian Research Council grants 230970 and 274711 and the
550 Swedish Research Council registration 2017-05268 [to FJWP], University of Zurich Research Priority
551 Program on Global Change and Biodiversity [to GS-S] and the US NSF grants OPP-1108425 and
552 PLR-1108425 [to PFS].

553

554 **Acknowledgements**

555 We thank John Gammon and Matthias Forkel for their very thoughtful and constructive reviews of
556 the manuscript. We thank the Inuvialuit and Greenlandic People for the opportunity to conduct field
557 research on their land.

558

559 **Data availability**

560 Data come from publicly available remote sensing and ecological datasets including:

561 MODIS (<https://modis.gsfc.nasa.gov/>), GIMMS3g.v1 (<https://nex.nasa.gov/nex/projects/1349/>), the

562 High Latitude Drone Ecology Network (<https://arcticdrones.org/>), shrub abundance, annual growth

563 ring and phenology datasets (<https://github.com/ShrubHub/QikiqtarukHub>,

564 <https://arcticdata.io/catalog/view/doi:10.18739/A24X0Q>,

565 <https://arcticdata.io/catalog/view/doi:10.18739/A28Q18>,

566 <https://arcticdata.io/catalog/view/doi:10.5065/D6542KRH>).

567

568 **Code availability**

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

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