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## Complexity revealed in the greening of the Arctic

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1 Complexity revealed in the greening of the Arctic

2

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79 **Editor's Summary**

80 The Arctic is rapidly warming and satellites are observing a greening of tundra ecosystems  
81 as plants respond to the warmer and longer growing seasons. This Perspective highlights  
82 the challenges of interpreting complex Arctic greening trends by combining ecological and  
83 remote sensing approaches.

84

85 **Abstract**

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

95

96 The Arctic has warmed at more than twice the rate of the rest of the planet in recent  
97 decades<sup>1,2</sup>. Over the past forty years, satellite-derived vegetation indices have indicated  
98 widespread change at high latitudes<sup>3-16</sup>. Satellite records allow for the quantification of  
99 change in places that are otherwise unevenly sampled by *in-situ* ecological observations<sup>17</sup>.  
100 Positive trends in satellite-derived vegetation indices (often termed Arctic greening)<sup>15</sup> are  
101 generally interpreted as signs of *in-situ* increases in vegetation height, biomass, cover and  
102 abundance<sup>5,18,19</sup> associated with warming<sup>5,14</sup>. In the most recent Intergovernmental Panel on  
103 Climate Change report, tundra vegetation change including greening trends derived from  
104 satellite records<sup>20</sup> was identified as one of the clearest examples of the terrestrial impacts of  
105 climate change. Large-scale vegetation-climate feedbacks at high latitudes associated with  
106 greening could alter global soil carbon storage and the surface energy budget<sup>21,22</sup>. In recent

107 years, slowing or reversal of apparent greening from satellite studies have been reported in  
108 some regions (sometimes termed Arctic browning)<sup>3,4,12,13,15,23,24</sup>. This slowdown is seemingly  
109 at odds with earlier responses to long-term warming trends<sup>3,25</sup>. Research now indicates  
110 substantial heterogeneity in vegetation responses to climate change in the Arctic<sup>18,19,26,27</sup>.  
111 However, the mechanistic links between satellite records and *in-situ* observations<sup>3,6,24</sup> remain  
112 unclear due to conceptual and technical barriers in their analysis and combined  
113 interpretation.

114

### 115 **A review of Arctic greening**

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

130

#### 131 *Vegetation indices as proxies of vegetation productivity*

132 Long-term trends in global vegetation dynamics are most commonly quantified from time  
133 series of spectral vegetation indices derived from optical satellite imagery (Figure 1). These  
134 indices are designed to isolate signals of leaf area and green vegetation cover from

135 background variation by emphasizing reflectance signatures in discrete regions of the  
136 radiometric spectrum<sup>6,29-32</sup>. Common vegetation indices include the Normalized Difference  
137 Vegetation Index (NDVI, Figure 2), Enhanced Vegetation Index (EVI) and Soil Adjusted  
138 Vegetation Index (SAVI), among others<sup>33-35</sup>. NDVI correlates with biophysical vegetation  
139 properties like Leaf Area Index (LAI) and the fraction of Absorbed Photosynthetically Active  
140 Radiation (fAPAR)<sup>14,36-39</sup>. However, these vegetation indices were not developed in polar  
141 contexts<sup>40</sup> and are only proxies of photosynthetic activity rather than direct measurements of  
142 biological productivity<sup>33,39,41</sup>. NDVI is the most commonly used vegetation index because it is  
143 simple to calculate with spectral bands monitored since the launch of early-generation Earth-  
144 observing satellites in the 1970s (Figure 2) and is perhaps best defined as a measure of  
145 above-ground vegetation greenness.

146

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

163 ecosystems, vegetation changes linked to spectral greening could include: encroachment of  
164 vegetation on previously non-vegetated land surfaces<sup>18,47</sup>, changes in community  
165 composition – such as tundra shrub expansion<sup>5,19,27</sup>, and/or changes in plant traits such as  
166 height<sup>48,49</sup>, leaf area, or phenology<sup>50–52</sup>. Tall shrub tundra typically has a higher NDVI than  
167 other tundra plant types<sup>49,53,54</sup>, and bare ground<sup>29</sup> has a much lower NDVI than vegetated  
168 tundra (Figure 2). Spectral browning could be related to a variety of factors including for  
169 example loss of photosynthetic foliage<sup>12</sup> or increases in bare ground cover due to permafrost  
170 thaw<sup>55</sup> (Figure 1). Thus, changes in the species composition, growth form and traits of plant  
171 communities can influence greening and browning trends.

172

### 173 *Physical factors influencing greening and browning trends*

174 Widespread non-biological changes in high-latitude ecosystems could confound and  
175 decouple spectral greening or browning trends from changes in plant productivity (Table 1).  
176 Land cover, topography, and associated soil moisture, surface water, land-surface  
177 disturbances and snow-melt dynamics can all influence the measured spectral greenness of  
178 landscapes<sup>56–63</sup> and likely influence greening trends. For example, changes in the extent of  
179 summer snow patches<sup>63</sup>, surface water<sup>60</sup> or surface soil moisture<sup>59</sup> that are often associated  
180 with landscape-scale topographic variation could influence the measured NDVI of the land  
181 surface. At high latitudes, optical satellite sensors are only effective for a short annual  
182 window due to the prolonged polar night, while low sun angles and persistent cloud cover  
183 reduce data quality in the summer season (Table 1). The unique physical properties of high-  
184 latitude ecosystems in addition to the constraints of polar remote sensing are often  
185 underemphasized in remote sensing studies of Arctic vegetation change.

186

### 187 *Arctic browning and heterogeneity of spectral greening trends*

188 Not all areas of the Arctic are spectrally greening (Figure 1), and in recent years spectral  
189 browning and heterogeneity of spectral greening trends have been highlighted<sup>3,4,12,13,23</sup>.  
190 Ecological explanations for vegetation browning include for example the sudden loss of



191 photosynthetically active foliage due to extreme climatic events<sup>64–67</sup>, biological interactions  
192 (e.g., disease or herbivore outbreaks)<sup>68–70</sup>, permafrost degradation<sup>23,55</sup> (Figure 1), increases  
193 in standing dead biomass<sup>71</sup>, coastal erosion<sup>72</sup>, salt inundation<sup>73</sup>, altered surface water  
194 hydrology<sup>74,75</sup> or fire<sup>9,76,77</sup>. Spectral browning, however, could be attributed to reduced  
195 productivity caused by adverse changes in growing conditions such as lower water  
196 availability, shorter growing seasons<sup>3</sup> or nutrient limitation<sup>27</sup>. Nonetheless, long-term spectral  
197 greening trends remain far more pervasive than spectral browning in tundra ecosystems.  
198 Figures vary from 42% greening and 2.5% browning from 1982 to 2014 in the GIMMS3g  
199 AVHRR dataset<sup>78</sup>, 20% greening and 4% browning from 2000 to 2016 in Landsat data<sup>15</sup> and  
200 estimates of 13% greening and 1% browning for the MODIS trends calculated for 1000  
201 random points in the tundra polygon in Figure 1 from 2000 to 2018. At circumarctic scales,  
202 the magnitude, spatial variability, and proximal drivers of patterns and trends of spectral  
203 greening versus browning are not well understood.

204

#### 205 *Correspondence between satellite and ground-based observations*

206 Evidence for correspondence among *in-situ* vegetation change and trends in satellite-  
207 derived vegetation indices is mixed<sup>47,79–81</sup>. NDVI trends across satellite datasets do not  
208 necessarily directly correspond with one another<sup>6,9</sup>, nor does any one sensor or vegetation  
209 index combination correspond directly with *in-situ* vegetation change<sup>47</sup>. For example, NDVI  
210 has been related to interannual variation in radial shrub growth<sup>5,10,82</sup>, yet how radial growth  
211 links to change in leaf area, aboveground biomass, or landscape measures of productivity is  
212 not always clear<sup>83–85</sup> (Figure 3). AVHRR NDVI greening trends did not correspond with the  
213 lack of change observed with Landsat NDVI data and *in-situ* plant composition between  
214 1984 and 2009 in North Eastern Alaska<sup>47</sup>. Direct comparisons of productivity changes from  
215 vegetation cover estimates<sup>18,86</sup>, biomass harvests<sup>53</sup> or shrub growth<sup>87</sup> are complicated by the  
216 lack of annual-resolution *in-situ* data and low sampling replication across the landscape. We  
217 attribute the mixed evidence for correspondence between *in-situ* and satellite-derived  
218 measures of tundra vegetation change and greening to the complexities of existing

219 terminology, challenges of interpretation of spectral vegetation indices at high latitudes, and  
220 the scaling issues as outlined below.

221

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

238

### 239 **Clarifying the terminology**

240 To distinguish spectral greening and browning events from longer-term trends, we propose  
241 clarified definitions of events and trends. For an individual pixel, we define the *spectral trend*  
242 as an increase or decrease in NDVI (or other spectral vegetation index) over decadal time  
243 scales and a *spectral event* as a temporal outlier in the vegetation index relative to the long-  
244 term trend. Trends should be determined using a Theil-Sen estimator or similar robust  
245 statistical test for analyses of satellite data<sup>30,101</sup>. We define a *spectral greening trend* as an  
246 increase of the vegetation index over decadal time scales. *In situ*, we interpret a *vegetation*

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

260

#### 261 *Differentiating events and trends*

262 In any measure of remotely sensed or field-based greening separate consideration of trends  
263 and events will increase ecological interpretability (Figure 5). Spectral greening and  
264 browning trends operate at any spatial scale, from localised patches to landscapes or even  
265 biome extents over decades. In contrast, spectral greening and browning events, such as  
266 those caused by vegetation dieback or rapid vegetation increase after disturbance, are often  
267 restricted to patch and regional scales over shorter durations. Events often have more  
268 limited extents relative to trends due to their proximal causes, like changes in herbivory or  
269 precipitation. Broader scale events are also possible (e.g. globally synchronized reductions  
270 in vegetation productivity caused by changes in insolation related to an intense volcanic  
271 eruption<sup>102</sup>). Therefore, greening or browning events might be embedded within overall  
272 spectral greening or browning trends, both temporally and/or spatially, without necessarily  
273 driving them (Figure 5). Examining the trend direction, magnitude and variance around the fit

274 over time can shape more detailed investigations into the ecological interpretation of Arctic  
275 spectral greening trends.

276

### 277 *The influence of baselines and temporal sampling*

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

297

### 298 **Challenges in the interpretation of vegetation indices**

299 In addition to the need for more clearly defined terms, challenges remain in the ecologically  
300 meaningful interpretation of long-term trends in optical satellite data, especially at high  
301 latitudes. The statistical relationship between a vegetation index and biomass, leaf area,

302 phenology, or any other measures of productivity can vary due to a suite of intrinsic (e.g.,  
303 sensor design, quality flagging algorithms), extrinsic (e.g., atmospheric conditions, sun  
304 angle, snow cover)<sup>6,106</sup> and biological factors<sup>107</sup> (Table 1). For example, the centre  
305 wavelength and width of spectral bands (e.g., in the red or near-infrared) used to generate  
306 vegetation indices were designed for different purposes in different sensors (Figure 2). While  
307 the NDVI formula may be the same, the covered spectral wavelength ranges differ between  
308 different datasets<sup>108</sup> (Figure 2b). Thus, the datasets may be more or less sensitive to specific  
309 non-vegetative influences, such as atmospheric scattering or the magnitude of spectral  
310 mixing associated with non-vegetated surfaces<sup>57</sup>. Spectral unmixing is the process of  
311 decomposing the spectral signature of a mixed pixel into the abundances of a set of  
312 endmember categories<sup>109</sup>. Longer-term vegetation change is difficult to resolve from cross-  
313 sensor comparisons among different satellite datasets or even among intercalibrations of the  
314 same sensor type (Figure 1). For these reasons, caution is warranted when comparing  
315 vegetation indices derived from different satellite products or even versions of the same  
316 product with different atmospheric corrections, quality assessments, and spatial/temporal  
317 compositing approaches<sup>6,108</sup>. Differences in NDVI signal processing are actively studied by  
318 the remote-sensing community (Table 1), but could be better accounted for or quantified in  
319 Arctic greening studies.

320

### 321 *Nonlinearities in NDVI as a vegetation proxy*

322 Direct interpretations of vegetation changes from spectral data are contingent on the local  
323 relationship between NDVI and *in-situ* vegetation. The statistical relationships between  
324 vegetation indices and measures of Arctic vegetation biomass are nonlinear<sup>29,110</sup> (Figure 2).  
325 This nonlinearity presents challenges for trend interpretation that are illustrated in Figure 2a.  
326 Here, an absolute increase in biomass for a 'low biomass' community towards a 'moderate  
327 biomass' community would result in a positive NDVI trend, but that same absolute biomass  
328 increase from moderate to high biomass would show virtually no trend in NDVI due to  
329 saturation (Figure 2). Thus, the relationship to common ecological variables like changes in

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

337

### 338 *Scaling issues in Arctic greening analyses*

339 Scale and hierarchies present a longstanding challenge in the interpretation of remotely-  
340 sensed vegetation proxies<sup>111-113</sup> (Figure 5). All long-term vegetation proxy time series  
341 (Landsat, MODIS, AVHRR) spatially aggregate spectral data to pixels (i.e., grains) that span  
342 hundreds of square metres to tens of square kilometres. The spectral signatures of plants  
343 and non-vegetative features in a landscape are reduced to a single value. The loss of  
344 variability within pixels masks information useful for the attribution of greening signals to  
345 processes across ecological hierarchies from populations and communities to ecosystems  
346 (Table 1, Figure 3 and 5). For example, within a single AVHRR GIMMS3g pixel, a  
347 subselection of 1 x 1 km pixels are upscaled to 8 x 8 km<sup>32</sup>. Within this aggregated pixel,  
348 ecological contributions to spectral greening signals such as increased shrub cover on  
349 south-facing slopes or revegetation of drained lake beds may be mixed with browning  
350 signals from for example disturbances such as retrogressive thaw slumps or vegetation  
351 trampling by herbivores (Figure 1). High-latitude pixels may also contain shadows caused by  
352 low-sun angle, patchy snow- and/or cloud-cover (Table 1). Thus, the emergent time series  
353 from such a pixel describes no single vegetation dynamic or environmental factor, but rather  
354 their integrated spectral responses. Broad-scale patterns of spatial variability in greening and  
355 browning across pixels are also influenced by grain size<sup>113</sup> (Figure 1, 2, 5). Higher resolution  
356 satellites such as Landsat can reduce, but not necessarily eliminate such spectral mixing<sup>15</sup>.  
357 However, the extent to which the sometimes-contradictory greening and browning signals

358 found across different spectral datasets can be attributed to the influence of the scale of  
359 measurement is poorly understood.

360

### 361 *Complexities of capturing phenology*

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

383

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

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

391

392 1. *Addressing scale issues by integrating proximal remote sensing and in-situ*  
393 *observations into pan-Arctic greening analyses*

394 Analyses of observations across scales will allow us to bridge the gap and improve our  
395 mechanistic understanding of the links between *in-situ* vegetation dynamics and broader  
396 remotely-sensed patterns and trends. New instruments for carrying out *in-situ* and proximal  
397 remote-sensing observations for comparison with satellite data are developing rapidly.  
398 However, we must urgently develop standardized field data collection protocols. In order to  
399 facilitate future synthesis, we need to incorporate data from long-term ecological  
400 monitoring<sup>12,18,86,94</sup>, historical imagery<sup>116</sup>, phenocam networks<sup>117</sup>, flux towers<sup>118</sup>, high-  
401 resolution imagery such as from aircraft, towers, and drones<sup>119</sup> and satellites.

402

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

405 New higher spatial or temporal resolution data will inform analyses of historic greening  
406 trends. Current panarctic Landsat analyses are shedding light on greening trends by  
407 exploiting higher spatial resolution data while accounting for the lower temporal resolution of  
408 observation records<sup>15</sup>. Recent and ongoing release of higher-resolution satellite datasets  
409 (e.g., EU-funded Sentinel missions, Digital Globe, Planet constellations) and data products  
410 (e.g., the Arctic Digital Elevation Model) will provide higher spatial (2-10 m) and/or temporal  
411 resolution (1-5 days) data across the Arctic<sup>120</sup>. We can gain a better understanding of past



412 spectral greening signals from legacy satellite datasets by conducting standardized  
413 reprocessing with for example statistical methods incorporating uncertainty in observations  
414 such as image quality information, improved atmospheric corrections and snow detection.

415

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

418 In addition to incorporating higher resolution datasets, new types of data collection can  
419 inform our understanding of what greening patterns and trends represent. New remote  
420 sensing campaigns using hyperspectral sensors or those that can measure Solar-Induced  
421 Fluorescence (SIF)<sup>121</sup> will provide new insights into vegetation dynamics. However, future  
422 sensor development across satellite, aircraft and near-surface platforms should be designed  
423 to maximize comparability. In addition to new data collection, novel data integration  
424 approaches, for example those employing machine learning, will provide greater insights into  
425 biome-scale analyses linking remote sensing observations with ecological change in high-  
426 latitude ecosystems<sup>21,122</sup>.

427

## 428 **Conclusions**

429 Recent research has highlighted the complexity in observed Arctic greening and browning  
430 trends. Although satellite data have been used to detect and attribute global change impacts  
431 and resulting climate feedbacks in Arctic ecosystems<sup>20,22</sup>, numerous questions and  
432 uncertainties remain. The three major challenges in resolving these uncertainties are: 1)  
433 improving the clarity of the definitions of widely used terminology associated with greening  
434 and browning phenomena, 2) promoting the understanding of the strengths and limitations of  
435 vegetation indices when making ecological interpretations and, 3) better incorporating and  
436 accounting for different scales of observation and uncertainty in analyses of changing tundra  
437 productivity and phenology. New sensors and better access to legacy data are improving our  
438 ability to remotely sense vegetation change. However, new data alone will not provide  
439 solutions to many of the longstanding conceptual and technical challenges. The complexity

440 of Arctic greening will only be fully understood through multidisciplinary efforts spanning the  
441 fields of ecology, remote sensing, earth system science and computer science. As a field,  
442 we need to look forwards to quantify contemporary and future change, but also backwards  
443 by conducting reanalyses of historical data. Ultimately, we urgently need a deeper  
444 understanding of the relationships between patterns and processes in greening and  
445 browning dynamics to improve estimates of the globally-significant climate change  
446 feedbacks in high-latitude ecosystems<sup>20</sup>.

447 Table 1. A variety of geophysical<sup>13,106,123</sup>, environmental<sup>44,60,61</sup> and ecological<sup>12,47,49,54,57,110</sup>  
 448 factors can influence the magnitude and direction of change in vegetation indices and are  
 449 particularly problematic at high latitudes<sup>6</sup>. The effects include: 1) Radiometric effects:  
 450 differences among satellite datasets including band widths, atmospheric effects, cloud-  
 451 screening algorithms, sensor degradation, orbital shift and bidirectional reflectance  
 452 distribution functions originating from differences in field of view and sun geometries. 2)  
 453 Spectral mixing: the blending of sub-pixel spatial heterogeneity that can influence the overall  
 454 pixel signal (Figure 2). 3) Adjacency effects: the reflectance of surrounding pixels that can  
 455 influence the signal of a given pixel (Figure 2). And, 4) a variety of environmental and  
 456 ecological factors from snow melt and soil moisture dynamics to composition of evergreen  
 457 versus deciduous or vascular versus non-vascular plants.

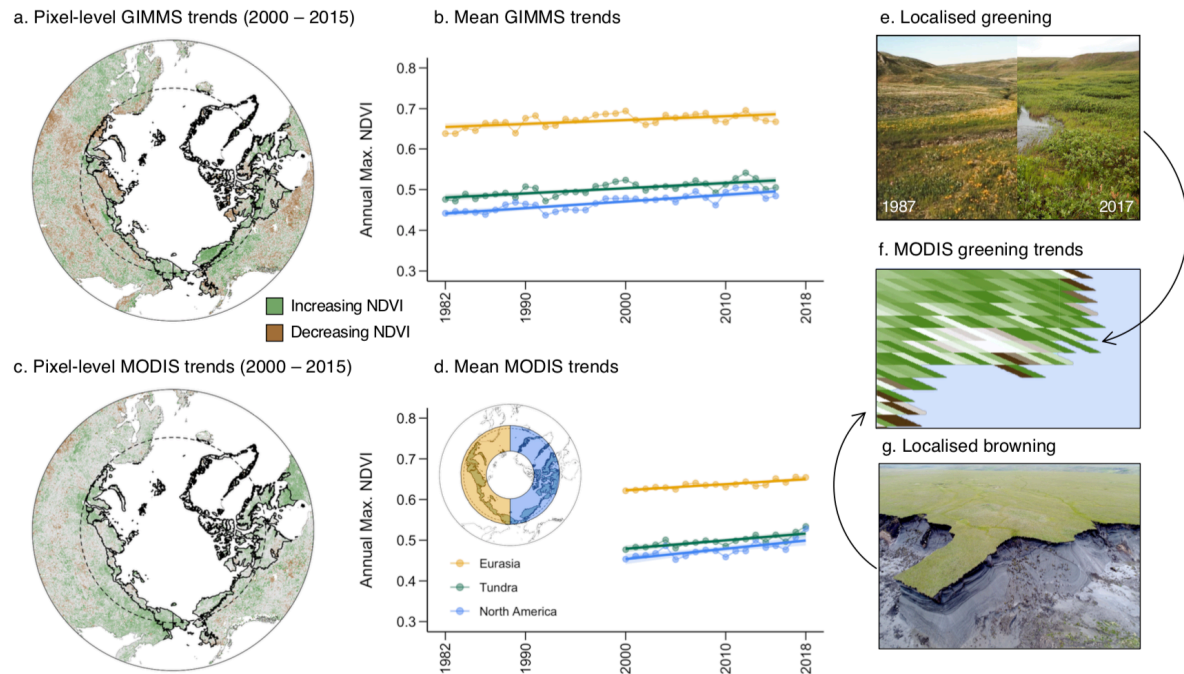
<b>Factors influencing vegetation indices</b>	<b>Specific effects</b>	<b>Influence on apparent greening patterns and trends</b>
Low sun angle	Radiometric effects	At high latitudes, low sun angles and cloud shadows can have a greater influence on vegetation indices relative to lower latitudes <sup>62</sup> . NDVI varies with sun angle, an effect magnified in spring and autumn <sup>62</sup> . Shadows also reduce NDVI and may be difficult to detect in coarse grained imagery <sup>44</sup> .
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 <sup>44</sup> . 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 <sup>44</sup> and/or sea ice conditions <sup>124</sup> .
Standing water	Spectral mixing, Adjacency effects	Standing water <sup>60</sup> 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 <sup>125</sup> . 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 <sup>56,57,60,125,126</sup> .
Snow patches	Spectral mixing, adjacency effects	Sub-pixel sized snow patches will decrease the NDVI for a given tundra area <sup>57</sup> . 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 <sup>57,63</sup> .
Soil moisture	Spectral mixing	Soil moisture can influence the reflectance of vegetated tundra surfaces <sup>58,59</sup> . NDVI values are sensitive to soil moisture, which may or may not covary with vegetation change <sup>125</sup> . Furthermore, NDVI is relatively insensitive to changes in very sparsely vegetated (e.g., the High Arctic <sup>127</sup> ) and very densely vegetated (e.g., forest or shrubland <sup>128</sup> ) environments.
	Plant water content	Mosses can absorb water and thus influence surface reflectance of landscapes independent of vascular plant phenology and productivity <sup>126</sup> .
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 <sup>126</sup> . 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 <sup>91</sup> . 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 <sup>50</sup> .
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 <sup>37,39</sup> (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 <sup>49,81</sup> . 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 <sup>107,126</sup> .

---

**Satellite records indicate greening trends across the circumpolar Arctic**



459

460 **Figure 1. Arctic greening varies across space and time and among satellite datasets**

461 **driven by both actual in-situ change and, in part, by the challenges of satellite data**

462 **interpretation and integration.** Trends in maximum NDVI vary spatiotemporally and the

463 magnitude of changes is different depending on what satellite imagery is analysed (a and c,

464 data subsetting to temporally overlapping years; b and d, GIMMS3gv1 1982 to 2015 and

465 MODIS MOD13A1v6 2000 to 2018). Regional trends may summarise localised greening, for

466 example shrub encroachment (e) and browning such as permafrost thaw (g) occurring at the

467 pixel scale on Qikiqtaruk - Herschel Island in the Canadian Arctic (f). NDVI trends (a and c)

468 were calculated using robust regression (Theil-Sen estimator) in the Google Earth Engine.

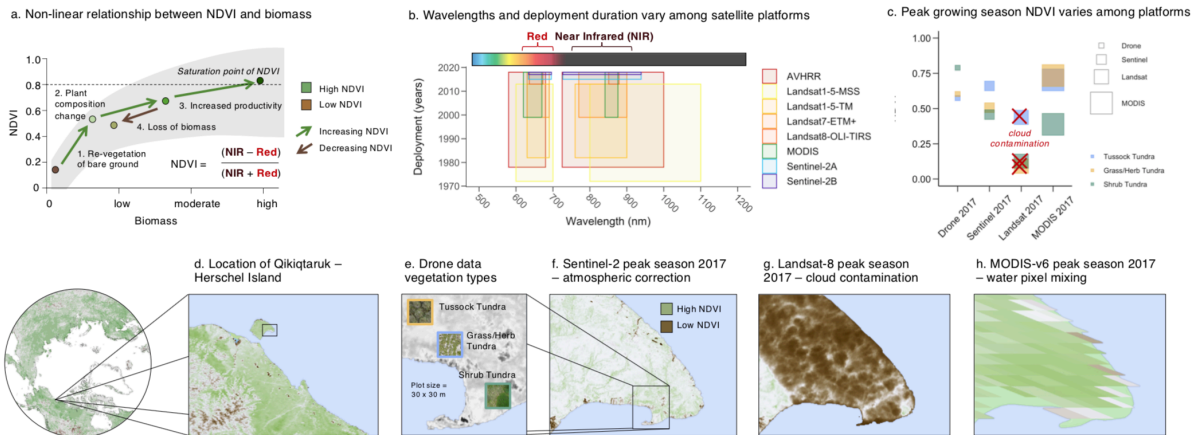
469 Dashed line indicates the Arctic Circle and the black outlined polygon (a and c) and green

470 'Tundra' line (b and d) indicates the Arctic tundra region from the Circum-Arctic Vegetation

471 Map ([www.geobotany.uaf.edu/cavm/](http://www.geobotany.uaf.edu/cavm/)). The inset map in d indicates the regions for the mean

472 trends for yellow 'Eurasia' and blue 'North America' polygons.

NDVI can vary across datasets due to NDVI biomass relationships, bandwidths of sensors and data quality issues



473

474

**Figure 2. Ecological interpretation of trends in the Normalized Difference Vegetation**

475

**Index (NDVI) requires a consideration of non-ecological factors.** NDVI, calculated as the

476

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

477

several common metrics of plant productivity, like biomass and LAI (a). Satellite platforms

478

have different spectral band widths which can influence calculations of peak of NDVI despite shared

479

centre wavelengths (b). NDVI values from commonly available satellite data products and

480

drone datasets (c) differed substantially across products and across plots of three different

481

vegetation types (e) during the period of peak biomass in 2017 on Qikiqtaruk – Herschel

482

Island, Yukon. Here, factors such as a lack of atmospheric correction (f), cloud or fog

483

contamination (g), sub-pixel mixing (h), different plot grain sizes of data in more or less

484

heterogeneous vegetation cover and timing of data acquisition could have all influenced

485

NDVI values. Data were analysed and extracted for 30 x 30 m plots from 13<sup>th</sup> July to 4<sup>th</sup>

486

August in 2017 using the Google Earth Engine for the MODIS MYD13A1v6 (pixel size = 500

487

m x 500 m) and Landsat 8 (pixel size = 30 m x 30 m) NDVI product, and the top-of-

488

atmosphere Sentinel-2 NDVI product without atmospheric corrections (pixel size = 10 m x 10

489

m) NDVI, and Pix4D-processed drone data collected using a radiometrically calibrated four-

490

band multispectral sensor (Sequoia, pixel size = 12 cm x 12 cm) on an FX-61 fixed-wing

491

platform with the High-latitude Drone Ecology Network protocols (<https://arcticdrones.org/>).

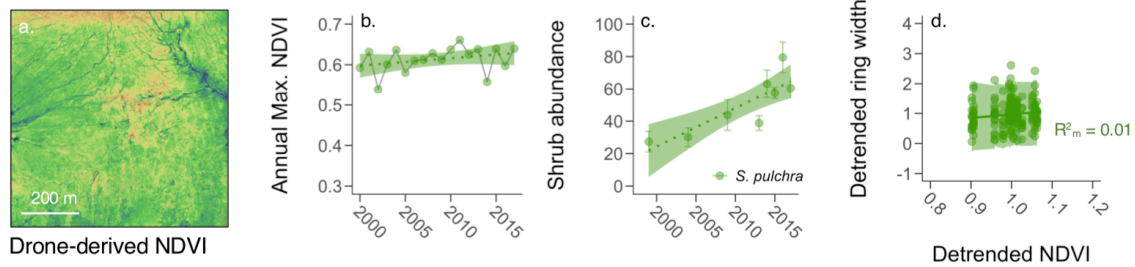
492

We purposefully present data with quality and processing issues above to highlight the

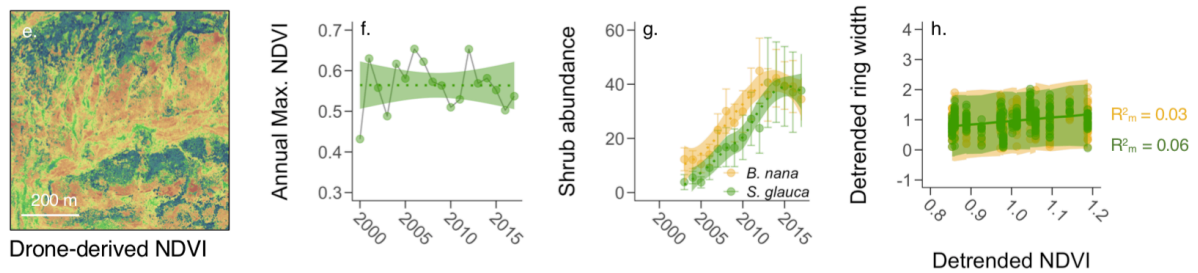
493 challenges in quantifying NDVI in regional-to-global studies where data quality issues may  
494 be spatially or temporally variable among locations.

### 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



495

496 **Figure 3. Sub-pixel spatial heterogeneity in vegetative greening and browning cannot**

497 **be accurately captured at coarser grains.** Landscape patterns (a, e), trends (b, f), and

498 variability (d, h) in NDVI may not represent *in-situ* observations of vegetation change. NDVI

499 trends and interannual variability had mixed correspondence with increases in shrub

500 abundance (c, g) and interannual variability in shrub growth on Qikiqtaruk – Herschel Island,

501 Yukon<sup>94</sup> (c, point framing in twelve 1-m<sup>2</sup> plots; d, *Salix pulchra* = 21,

502 <https://github.com/ShrubHub/QikiqtarukHub>) and Kangerlussuaq, Greenland<sup>84,129</sup> (g, 13

503 0.25-m<sup>2</sup> plots; H, *Betula nana* = 42, *Salix glauca* = 32,

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

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

506 <https://arcticdata.io/catalog/view/doi:10.5065/D6542KRH>). Errors are standard error bars

507 around mean values (c, g) and 95% credible intervals for a Bayesian hierarchical model of

508 the relationship between detrended annual growth rings and NDVI with shrub individual and

509 year as random effects (d, h). Detrending was done using a spline fit from the dplR package

510 in R. Credible intervals for model slopes overlapped with zero (d, h). Marginal R<sup>2</sup> values

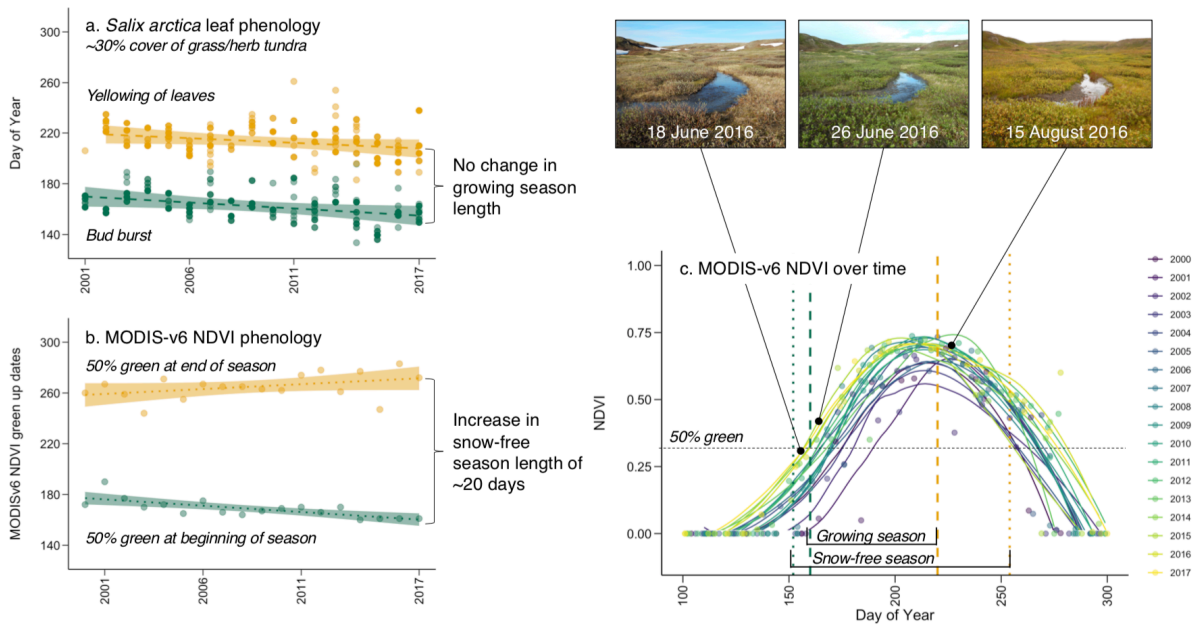
511 indicate the variance in detrended ring widths explained by detrended NDVI (d, h).

512 Landscape NDVI patterns (a and f) were measured using a Parrot Sequoia and FX-61 fixed



513 wing platform according to High-latitude Drone Ecology Network protocols in the summer of  
514 2017 (<https://arcticdrones.org/>) and analysed using the Pix4D software. Coarser-grain NDVI  
515 time series (MODIS MOD13A1v6, 500m pixels) were calculated using Google Earth Engine  
516 and the Phenex package in R.

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



517

518 **Figure 4. Satellite-derived phenology estimates do not always match with in-situ plant**

519 **phenology observations.** Satellite-observed snow-free season length of the land surface

520 (here defined as the period with NDVI greater than 50% of the max NDVI, b and c) might not

521 directly correspond to the growing season of vascular plants in tundra ecosystems,

522 particularly in autumn (a). Snow-melt dynamics can obscure the plant phenology signal and

523 non-vascular or evergreen plants can obscure the deciduous vascular plant seasonal signal.

524 Plant phenology data were collected at 20 monitoring plots on Qikiqtaruk-Herschel Island for

525 the species *Salix arctica*, which makes up approximately 30% of the cover in the grass- and

526 forb-dominated vegetation type. Analyses indicate that both leaf emergence and senescence

527 have become earlier, resulting in no change in realized growing season length despite

528 substantial increases in the snow-free period of the land surface<sup>94</sup> (a – c,

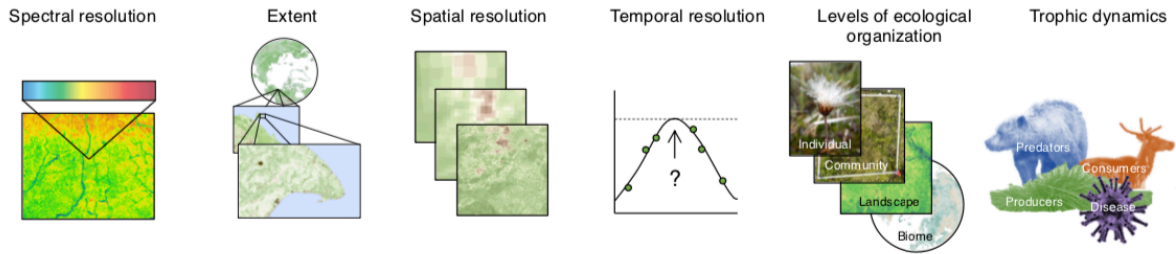
529 <https://github.com/ShrubHub/QikiqtarukHub>). Satellite data are MODIS MOD13A1v6

530 extracted for the pixel containing the phenology transects using Google Earth Engine and

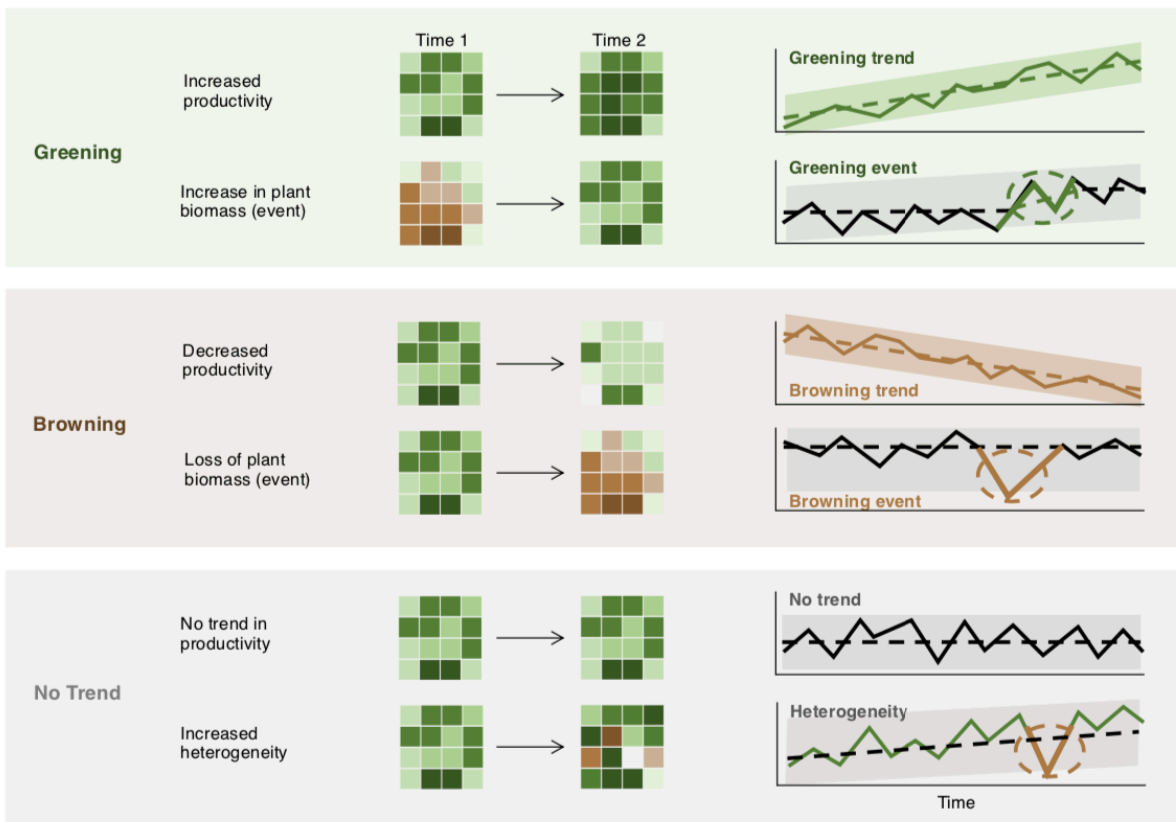
531 the Phenex package in R (b and c).

**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



532

533 **Figure 5. Arctic greening is influenced by both issues of measurement scale and**

534 **inference across ecological hierarchies.** Spectral resolution (Figure 2), extent (Figure 1),

535 spatial resolution (Figure 2), landscape-level heterogeneity (Figure 3), temporal resolution

536 (Figure 4), and ecological factors all influence the interpretation of greening trends (a).

537 Within-pixel changes in land surface greening and browning events and trends can translate

538 into different greening and browning patterns as their effects are scaled up (b). Ecological

539 processes that comprise greening and browning trends include a combination of events,

540 such as a pulse of plant recruitment or growth, a dieback of plants due to an extreme winter

541 climate event, herbivore or disease outbreak or other disturbance and subsequent recovery.  
542 Longer-term change such as increasing shrub cover or progression of permafrost  
543 disturbances can also influence real-world NDVI time series. These different factors add  
544 complexity to the interpretation of Arctic greening trends. The scale and hierarchy of  
545 observations need to be incorporated into and/or accounted for in future analyses of Arctic  
546 greening.

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550

551 **Author Contributions**

552 IHM-S and JTK conducted the analyses and wrote the manuscript with contributions from all  
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557 of Arctic Browning Workshop' at the University of Sheffield led by GKP.

558

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586

## 587 **Data availability**

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

589 MODIS (<https://modis.gsfc.nasa.gov/>), GIMMS3g.v1

590 (<https://nex.nasa.gov/nex/projects/1349/>), the High Latitude Drone Ecology Network

591 (<https://arcticdrones.org/>), shrub abundance, annual growth ring and phenology datasets

592 (<https://github.com/ShrubHub/QikiqtarukHub>,

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

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

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

596

## 597 **Code availability**

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

599

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