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1 **Velocity of change in vegetation productivity over northern high latitudes**

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22 Warming is projected to increase the productivity of northern ecosystems¹⁻³. However,
23 knowledge on whether the displacement of vegetation productivity isolines matches the
24 northward motion of temperature isolines is still limited. Here, for the first time, we
25 compared changes in the spatial patterns of vegetation productivity and temperature
26 using the concept of velocity of change, which is defined as the ratio of temporal changes
27 in a variable to the spatial gradient of the same variable, making it possible to express
28 these two variables in the same unit of displacement per time⁴⁻⁹ (e.g. km yr⁻¹). Normalized
29 Difference Vegetation Index (NDVI) data from 1982 to 2011 was used to calculate the
30 velocity of vegetation productivity north of 50°N. Our results show that the average
31 velocity for growing season (GS) NDVI (NDVI_{GS}; 2.8±1.1 km yr⁻¹) is lower than that for
32 GS mean temperature (T_{GS}; 5.4±1.0 km yr⁻¹). About 20% of the study area display larger
33 velocities of NDVI_{GS} than T_{GS}, mainly in eastern Europe, northeastern and southern
34 Siberia, and parts of western Canada. By comparison, in northern Europe, western and
35 central Siberia, and northeastern Canada (52% of the study area), the NDVI_{GS} velocity is
36 less than half of T_{GS} velocity, indicating that the northward motion of productivity isolines
37 is much slower than that of temperature isolines over the last 30 years. We tentatively
38 attribute this mismatch between the velocities of vegetation productivity and temperature
39 to the effects of limited resource availability and vegetation acclimation mechanisms.
40 Analyses of the velocity of ecosystem productivity from ecosystem model simulations
41 further suggested that limited nitrogen availability is a crucial obstacle for vegetation to
42 track the warming trend.

43

44 The Earth's climatic system is experiencing significant warming, which has raised concerns
45 about the impacts on terrestrial ecosystems¹⁰. In-situ observations, manipulative experiments,
46 as well as satellite-derived data have all pointed out that vegetation productivity is sensitive to
47 temperature change in northern high latitudes^{1,11-14}.

48

49 Vegetation can adjust to climate change through relatively fast mechanisms (e.g. adjustment of
50 phenology or physiology^{15,16}) and through slower mechanisms (e.g. phenotypic and genotypic
51 adaptations, changes in community composition¹⁶). If climate changes slowly and vegetation
52 has ample time to adjust, it can be expected that warming would result in a northward shift of
53 vegetation structure and function in the northern hemisphere. In reality, temperature acclimation
54 and adaptation of plants¹⁷, as well as limited resource availability such as nitrogen¹⁸, may
55 prevent vegetation productivity change from keeping the same rate as the rapid climate
56 warming. To the contrary, CO₂ fertilization effects and regional nitrogen deposition may
57 amplify the greening trend induced by warming temperature^{3,19}. Unfortunately, knowledge
58 about the rate at which vegetation responds to ongoing temperature change is still limited. In
59 particular, it is not known whether and to what extent change in the spatial displacement of
60 vegetation productivity isolines during recent decades matches the northward motion of
61 temperature isolines.

62

63 The concept of velocity of change⁹ offers the opportunity to directly compare the ongoing
64 change in the spatial patterns of temperature and productivity. This concept was first developed
65 for climate impact research to compare the displacement rate of a forcing variable (e.g.
66 temperature) with that of an impacted variable (e.g. the occurrence of a given species) by
67 converting them into the same units^{4-9,20} (e.g. km yr⁻¹). The velocity of change in a geospatial
68 variable is the ratio of its temporal change to its local geographical gradient^{5-7,21,22}. Imagine, for

69 instance, that the mean spring temperature has increased by 0.3°C over 30 years. At the same
70 location, a 1°C temperature spatial gradient is observed across a 100 km distance with a south-
71 to-north decrease in temperature. The velocity of spring temperature change is then 1 km yr^{-1}
72 for this example (temporal trend of 0.3°C over 30 years, divided by the spatial gradient of 1°C
73 over 100 km).

74

75 In a similar manner, within the boundaries of a biome, we can calculate the velocity of change
76 in vegetation productivity (also in km yr^{-1}). For each local cell, plant productivity responds to
77 the changes in ambient environment condition, whether the responses are through changes in
78 phenology or physiology of plant individuals (in-situ), or changes in community composition
79 (e.g. shrub expansion). Such changes in productivity for each of the multiple pixels over a
80 region eventually appear as the movement of productivity isolines at regional scale
81 (Supplementary Figure 1a). In this case, the velocity of productivity change indicates a
82 displacement in the isolines of this variable due to changes in productivity in response to climate
83 change for multiple pixels over a certain region (Supplementary Figure 1b). In another word,
84 the concept of velocity here quantifies how the spatial pattern of vegetation productivity
85 changes in response to environmental changes during the study period, with different speeds
86 and directions for each pixel. For a certain location with a south-to-north decrease in vegetation
87 productivity, a northward velocity of vegetation productivity of 1 km yr^{-1} over the past 30 years
88 would indicate that the current productivity of a certain ecosystem has increased from its value
89 30 years ago to a higher value today equaling to the past productivity of another ecosystem
90 which is 30 km ($1\text{ km yr}^{-1}\times 30\text{ years}$) south of the target one. The comparison between the
91 velocities of change in vegetation productivity and temperature then makes it possible to
92 identify if the motion of productivity isolines is in the same directions of that of temperature
93 isolines, or / and if the displacement of productivity isolines is faster/slower than that of

94 temperature isolines. Then we can address the question of whether and to what extent changes
95 in the spatial pattern of vegetation productivity during recent decades have matched the
96 displacement of temperature isolines (Supplementary Information S1.1).

97

98 In this study, we mapped for the first time the vector (both velocity and direction) of change in
99 vegetation productivity calculated using satellite-derived long-term Normalized Difference
100 Vegetation Index (NDVI). The NDVI dataset covers the period of 1982-2011 and was analyzed
101 for velocity in the region north of 50°N, where vegetation productivity responds mainly to
102 temperature changes^{23,24}. Productivity velocities were then compared to those of temperature
103 change (see Methods). To minimize the covariate effects of other environmental variables, our
104 analyses focused only on the overlap of natural ecosystems (defined following the International
105 Geosphere-Biosphere Program; see Methods; Supplementary Figure 2) and ecosystems where
106 productivity is temporally positively ($p < 0.1$) correlated with temperature during the study
107 period (see Methods; Supplementary Figure 3). This study area represents about 76% of the
108 vegetated area (annual mean NDVI > 0.1) over the northern high latitudes.

109

110 We first calculated the distribution of the velocities and their directions for the sum of the April
111 to October growing season (GS) NDVI (NDVI_{GS}) and GS mean temperature (T_{GS}) over the last
112 30 years (see Methods). The average NDVI_{GS} velocity is 2.8 ± 1.1 km yr⁻¹ over the study area.
113 Large NDVI_{GS} velocities (>10 km yr⁻¹) are found in eastern Europe, northeastern and western
114 Siberia, and low values (<1 km yr⁻¹) in central and eastern Canada as well as western Siberia
115 (Fig. 1a). In 89% of the study area, the directions of NDVI_{GS} vectors are from regions with
116 higher NDVI_{GS} values to those with lower values, with the majority of the study area (55%)
117 showing a northward movement (Fig. 1c). On average, T_{GS} velocity over the study area (5.4 ± 1.0
118 km yr⁻¹) is nearly twice the NDVI_{GS} velocity. The largest T_{GS} velocities (>10 km yr⁻¹) are

119 observed in northern central and eastern Siberia, parts of Europe, as well as eastern and
120 northeastern Canada, whereas low values ($<1 \text{ km yr}^{-1}$) are found only in southwestern Canada
121 (Fig. 1b). Northward T_{GS} vectors are observed in 71% of the study area (Fig. 1d).

122

123 Comparing the vectors of $NDVI_{GS}$ and T_{GS} (see Methods), we found that, across the study area,
124 91% of the study area show a positive ratio between the velocities of projected $NDVI_{GS}$ vectors
125 and the velocities of T_{GS} vectors ($V_N:V_T$ ratio) (blue color in Fig. 1e). This suggests that in these
126 regions, vegetation productivity has tracked the direction of temperature change during the
127 study period. Among these regions, about 98% of the area show positive trends in both $NDVI_{GS}$
128 and T_{GS} , that is, vegetation productivity has increased where temperature warmed. Only a few
129 regions in western Canada with positive $V_N:V_T$ ratio show decreasing $NDVI_{GS}$ as a result of
130 decreasing T_{GS} during the study period (Supplementary Figure 4). Larger $NDVI_{GS}$ velocities
131 (projected along the T_{GS} velocities) than T_{GS} velocities occur in 20% of the whole study area,
132 mainly in eastern Europe, northeastern and southern Siberia, as well as parts of western Canada
133 (Fig. 1e). In about half of the study area, the $V_N:V_T$ ratio is lower than 0.5, in particular northern
134 Europe, central Siberia, and northeastern Canada. Similar results are also obtained when using
135 different climate forcing datasets, when choosing different GS definitions (May to September
136 or April to September), or when $NDVI_{GS}$ velocities were compared with those of mean annual
137 temperature (Supplementary Figure 5; see also Methods).

138

139 Overall, the largest $V_N:V_T$ ratios are found in relatively warmer regions (Supplementary Figure
140 6; $R=0.89$, $p<0.01$). Several possible reasons may explain this phenomenon. First, the
141 ubiquitous CO_2 fertilization effect, which can amplify the warming-induced positive trend of
142 productivity³, is expected to be relatively stronger at higher temperature^{25,26}. Second, larger
143 $V_N:V_T$ ratios in warmer regions may arise from larger nitrogen availability, either from

144 increased soil nitrogen mineralization or from additional nitrogen deposited to ecosystems in
145 most of the warmer temperate regions of the northern hemisphere^{27,28}. In addition, the lower
146 $V_N:V_T$ ratios found in colder climates may be associated with background limitations induced
147 from the presence of permafrost (Supplementary Figure 7). Permafrost constrains the
148 development of roots, and slows down the decompositions of soil organic matter limiting
149 mineral nitrogen and phosphorus availability for plants²⁹.

150

151 In general, vegetation productivity north of 50°N is mainly limited by two factors: growing
152 season length and growing season maximum photosynthetic capacity^{24,30}. Growing season
153 length is determined by the start of the growing season (SOS) and the end of the growing season
154 (EOS), which are closely associated with temperature²³, while peak growing season
155 photosynthetic capacity can be partly reflected by the maximum NDVI in the growing season
156 (MOS), which is jointly controlled by nutrient availability and temperature for the study area³¹.
157 Hence, we analyzed separately the vectors of NDVI-derived SOS, EOS, and MOS, respectively
158 (see Methods), as shown in Fig. 2.

159

160 The average velocity of change in the SOS date during 1982-2011 is $3.6 \pm 1.0 \text{ km yr}^{-1}$ over the
161 study area. Pronounced differences in both velocity and direction of SOS vectors can be seen
162 between Eurasia and North America in Fig. 2a and 2d, respectively. The majority of Eurasia
163 (74%) show northward SOS vectors (related to the advance in spring phenology), while only
164 half of North America display northward SOS vectors (Fig. 2d). In Eurasia, the velocity of SOS
165 vectors exceeds 5 km yr^{-1} in 61% of the whole area, whereas in most of North America (73%
166 of the continent area north of 50°N), it is lower than 5 km yr^{-1} (Fig. 2a). The largest SOS
167 velocities ($>20 \text{ km yr}^{-1}$) are observed in northeastern Siberia. This area also experiences the
168 largest ($>10 \text{ km yr}^{-1}$) velocities of springtime (March to May, MAM) temperature increase

169 (Supplementary Figure 8a). In addition, we found that about one third of the study area shows
170 larger velocities of SOS vectors (projected along the spatial gradient of spring temperature)
171 than those of spring temperature vectors themselves (Fig. 2g). These regions include central
172 Europe, central and southern Siberia, as well as parts of eastern and northwestern Canada. By
173 contrast, in western and northeastern Siberia, the velocities of projected SOS vectors are smaller
174 than those of the vectors of springtime temperature (ratio<0.5). Moreover, for 17% of the study
175 area, mainly in Canada, the SOS vectors do not parallel the direction of temperature vectors
176 (red color in Fig. 2g). In eastern and central Canada, a delayed SOS date occurs with warming,
177 whereas in western Canada, an earlier SOS date occurs despite the cooling trend of spring
178 temperature (Supplementary Figure 9a and 10a). Such mismatches may be attributed to changes
179 in the relationship between heat requirement and chilling accumulation (the duration and/or
180 sum of cold temperature during dormancy) due to changes in the late-winter and spring
181 temperature³²⁻³⁴.

182

183 It has been reported that the temperature sensitivity of EOS is lower than that of SOS, because
184 changes in EOS are co-limited by other factors than temperature^{31,35,36} (e.g., photoperiod and
185 soil moisture). At first sight, our analysis of EOS velocities suggests the opposite result: the
186 average EOS velocity across the study area ($6.0 \pm 1.1 \text{ km yr}^{-1}$) is nearly twice the SOS velocity
187 ($3.6 \pm 1.0 \text{ km yr}^{-1}$) during 1982-2011. Nearly 60% of the study area display EOS velocities larger
188 than 5 km yr^{-1} (Fig. 2b). However, change in mean temperature from August to October displays
189 a much higher average velocity ($7.1 \pm 1.0 \text{ km yr}^{-1}$) than that in spring temperature ($3.7 \pm 1.0 \text{ km}$
190 yr^{-1}), rendering their average warming dependency more similar. In any case, the co-regulation
191 of EOS by other factors likely explains the much more heterogeneous pattern of the directions
192 of EOS vectors (Fig. 2e) than that of SOS vectors (Fig. 2d). Comparing EOS and August to
193 October mean temperature vectors, we found that regions where the velocities of projected EOS

194 vectors exceed those of the original temperature vectors are located mainly in southern Siberia
195 as well as in northeastern and southwestern Canada, accounting for 36% of the study area (Fig.
196 2h). By contrast, northeastern Siberia and eastern Canada experience very strong warming
197 during August-October (Supplementary Figure 10b), but the EOS vectors in these regions show
198 generally lower velocity than in southeastern Siberia (Fig. 2b), resulting in a smaller ratio (<0.5)
199 of EOS to autumn temperature change velocities (Fig. 2h). In parts of central Siberia and
200 western Canada, we even observe an advanced EOS date with warming temperature (red color
201 in Fig. 2h). This mismatch between the vectors of EOS and temperature change may be partly
202 explained by the decreased solar radiation in these regions³⁶. Since it has been suggested that
203 increases in solar radiation suppress the accumulation of abscisic acid and subsequently slow
204 the speed of leaf senescence³⁷, the decline in solar radiation may have resulted in advanced
205 EOS dates despite the warming temperature.

206

207 On average, the northern high latitudes exhibit an average MOS velocity of $3.1 \pm 1.0 \text{ km yr}^{-1}$
208 over the past three decades, which is lower than that of summer (June to July) temperature
209 ($4.2 \pm 1.1 \text{ km yr}^{-1}$). MOS velocities larger than 10 km yr^{-1} are found in eastern Europe,
210 northeastern Siberia and northeastern Canada, while values lower than 1 km yr^{-1} mainly appear
211 in the southern part of central Siberia, as well as in central and eastern Canada (Fig. 2c).
212 Comparison between the velocity of MOS vectors (projected along the spatial gradient of
213 summer temperature) and that of summer temperature vectors (Fig. 2i) show that larger MOS
214 than temperature change velocities mainly occur in eastern Europe, northeastern Siberia, as well
215 as in western and northeastern Canada, accounting for one third of the area where changes in
216 MOS have tracked the direction of the temperature change (blue color in Fig. 2i). In
217 northwestern Europe and southern Siberia, however, MOS velocities are generally less than
218 half of summer temperature velocities. Since northern ecosystems are strongly temperature-

219 limited², the slower velocities of projected MOS vectors compared to summer temperature
220 velocities may be partly attributed to the fact that photosynthesis at the peak of the growing
221 season is constrained because the low-temperature-induced nutrient limitations do not allow the
222 development of dense canopies³⁸. Interestingly, we found larger MOS velocities in shrub and
223 tundra ecosystems ($3.4 \pm 1.0 \text{ km yr}^{-1}$ on average) (vegetation types from the International
224 Geosphere-Biosphere Program; Supplementary Figure 2) than in other vegetation types. Also
225 the ratio of velocities of projected MOS vectors to summer temperature velocities is highest in
226 shrub and tundra (Supplementary Table 1). Warming-induced tall shrub and tree expansion³⁹
227 may be responsible for the larger MOS velocities in shrub and tundra than in other terrestrial
228 ecosystems.

229

230 Land surface models are used to project future responses of ecosystems to climate change and
231 to analyze the contribution of different driving factors⁴⁰. We therefore examined the vectors of
232 change in vegetation productivity using simulated net primary productivity (NPP) from five
233 process-based land surface models (CLM4.5, LPJG, OCN, ORCHIDEE, and VEGAS; see
234 Methods and Supplementary Table 2). Our results show that the ensemble model-mean of
235 change in annual NPP displays an average velocity of $4.0 \pm 1.3 \text{ km yr}^{-1}$ (\pm standard deviation
236 across models). The highest NPP velocity values ($>10 \text{ km yr}^{-1}$) are found in southern and
237 northeastern Siberia (Supplementary Figure 11a). We next compared the velocities of simulated
238 NPP with those of NDVI_{GS} after projecting both NPP and NDVI_{GS} vectors along the spatial
239 gradient of T_{GS} (see Methods). The results show that, on average, about 60% of the study area
240 (ranging from 47% to 70% across different models) show higher velocities of simulated NPP
241 than of NDVI_{GS}. Further, we examined the NPP velocities using a satellite-derived terrestrial
242 NPP product (GIMMS_{3g} NPP; see Methods), which display spatial patterns consistent with
243 those of the NDVI_{GS} vectors (for both velocity and direction), albeit with generally lower

244 velocity across the study area (Supplementary Figure 12). Compared with the GIMMS_{3g} NPP,
245 the model-simulated NPP produces larger velocity in about 71% (ranging from 61% to 81%) of
246 the study area. This mismatch regarding the increase in productivity under warming between
247 model- and satellite-based estimates may partly be explained by the limited availability of
248 nitrogen in these regions⁴¹, which is suggested to prevent changes in vegetation productivity
249 from adequately tracking the warming trend, but are not accounted for in some of the models⁴².
250 Interestingly, we found that the two models with nitrogen limitations and nitrogen deposition
251 taken into consideration (CLM4.5 and OCN) both produce lower NPP velocities (1.7 ± 1.0 km
252 yr^{-1} and 2.0 ± 1.1 km yr^{-1} for CLM4.5 and OCN, respectively) than those without a coupled
253 nitrogen cycle (3.5 ± 1.0 km yr^{-1} , 2.9 ± 1.1 km yr^{-1} and 4.7 ± 1.2 km yr^{-1} for LPJG, ORCHIDEE
254 and VEGAS, respectively) (Supplementary Table 3). Similar results are also observed for gross
255 primary productivity (GPP; Supplementary Table 3 and Figure 13).

256

257 In summary, in this study we applied the concept of velocity to remotely sensed NDVI fields
258 and compared the NDVI velocity to that of temperature in northern (predominantly temperature
259 limited) ecosystems north of 50°N. The average velocity of change in NDVI_{GS} (2.8 ± 1.1 km yr^{-1})
260 over the study area is only about half of that in T_{GS} (5.4 ± 1.0 km yr^{-1}). A mismatch between
261 the NDVI_{GS} and T_{GS} velocities suggests that the ratio of sensitivities of productivity to
262 temperature across space and in time is not equal to one (Supplementary Information S2.1).
263 Our analyses thus combined time and space and to some extent challenged the space-for-time
264 substitution hypothesis⁴³ as applied in several studies using spatial gradients to back-cast
265 temporal changes. Moreover, such a mismatch between productivity and temperature velocities
266 suggests a disequilibrium in the plasticity of vegetation productivity changes to tail off with the
267 spatial spread of warming. This may due to the prevalence of background spatial limitations by
268 other factors limiting vegetation productivity such as soil moisture and nutrients¹⁸, which also

269 correspond to vegetation acclimation to the ongoing warming¹⁷, as well as the transient
270 limitations in the rate of adjustment of plant response to the warming rate in different seasons.
271 In addition, differences in the magnitudes of the SOS, EOS and MOS velocities suggest that
272 the seasonal profile of vegetation growth has strongly re-shaped over time and that limitations
273 may be expected in spring phenology not being able to track temperature moving northward
274 (e.g. for photoperiod limitations, chilling requirements reasons³²⁻³⁴).

275

276 **Methods**

277 **Data.** The monthly air temperature data set used in this study is the CRU TS 3.22 climate data
278 set obtained from Climatic Research Unit (CRU) for the period January 1982 to December 2011
279 (<http://www.cru.uea.ac.uk/cru/data/hrg/>). We also used WATCH Forcing Data Methodology to
280 ERA-Interim data with temporal resolution of 3 hour (WFDEI)⁴⁴. The third generation Global
281 Inventory Monitoring and Modeling System Normalized Difference Vegetation Index (GIMMS
282 NDVI_{3g}) data set from the Advanced Very High Resolution Radiometer (AVHRR) sensors was
283 downloaded from <http://ecocast.arc.nasa.gov/data/pub/gimms/3g.v0/>. The data set has 15-day
284 temporal frequency from July 1981 to December 2011 with a spatial resolution of 8 km⁴⁵. Only
285 positive NDVI values from January 1982 to December 2011 were used in this study. We also
286 used a 16-day NDVI datasets retrieved using observations from Terra Moderate Resolution
287 Imaging Spectroradiometer (MODIS) (MODIS NDVI) from February 2000 to July 2012 with
288 spatial resolutions of 1 km⁴⁶ to test the robustness of the analyses conducted with GIMMS
289 NDVI_{3g} data. A 30-year (1982-2011) satellite-derived terrestrial net primary productivity (NPP)
290 data set presented in a recent study⁴⁷, which was calculated using GIMMS leaf area index (LAI)
291 and fraction of photosynthetically active radiation absorbed by the vegetation (FPAR) based on
292 MODIS NPP algorithm⁴⁷, was also used. Note that the spatial structures of the error in the
293 surfaces of NDVI and temperature may be different due to different approaches to obtain

294 gridded datasets. For example, the NDVI differences between neighboring cells obtained from
295 composite AVHRR images may be more contrasted than those of climate data being obtained
296 by interpolation of station data or re-analysis with numerical weather prediction models. To
297 reduce the effect of fine scale spatial structure in the errors on each surface, all the data have
298 been regridded into a common $1^{\circ}\times 1^{\circ}$ grid. A mask is applied whereby grid cells where annual
299 mean NDVI is less than 0.1 are excluded to remove areas with very low ecosystem productivity.
300 Vegetation types defined following the International Geosphere-Biosphere Program based on a
301 MODIS land cover classification
302 (http://webmap.ornl.gov/wcsdown/wcsdown.jsp?dg_id=10011_1) were used to further remove
303 hardly natural and non-natural vegetation lands.

304

305 **Satellite-derived indexes of vegetation productivity.** The maximum NDVI value at each
306 bimonthly time step was used to calculate monthly NDVI in order to minimize the effects of
307 atmospheric water vapor, non-volcanic aerosols and cloud-cover⁴⁵. The growing season (GS)
308 NDVI (NDVI_{GS}) was calculated as the sum of monthly NDVI values from April to October. GS
309 defined as May to September and April to September were also used for robustness test. Note
310 that over the northern high latitudes, calculating NDVI_{GS} with a predefined period is to some
311 extent challenging in the boreal regions because of the snow effect. Therefore, we calculated
312 the percentage of the study area with possible snow effects using the quality flag information of
313 GIMMS NDVI_{3g} datasets⁴⁵. To be specific, when regridding the original 8 km ($\approx 1/12$ degree)
314 monthly data into a $1^{\circ}\times 1^{\circ}$ gridded monthly data, a $1^{\circ}\times 1^{\circ}$ pixel is considered to be affected by
315 snow in this month if less than 70% pixels within a 12×12 pixel window have a flag value of 1
316 or 2 (good value). For each year, a pixel is then considered to be affected by snow if more than
317 2 months during the predefined growing season (e.g. April-October) is affected by snow.
318 Finally, we defined regions with snow effects as pixels with more than 9 years showing snow

319 effects during the study period. The results show that regions affected by snow are mainly
320 located in Alaska, northern Europe and parts of eastern Siberia, accounting for only 12% of the
321 study area (red color in Supplementary Figure 14).

322

323 Two phenological indexes were derived from GIMMS NDVI_{3g} data set: the start of growing
324 season (SOS, DOY) and the end of growing season (EOS, DOY). The SOS date was calculated
325 as the averaged SOS date estimated by four different methods: Timesat, Spline, Hants and
326 Polyfit⁴⁸⁻⁵⁰. The EOS date was obtained from the averaged EOS estimated by four different
327 methods: Hants, Polyfit, Double Logistic and Piecewise Logistic³⁶. For each year during 1982-
328 2011, the maximum NDVI of growing season (MOS) was calculated as the peak NDVI value
329 among monthly NDVI values during the growing season, which was defined based on the
330 month when the SOS and EOS date occurred.

331

332 **Model-simulated ecosystem productivity.** We used NPP and gross primary productivity (GPP)
333 outputs from 1982 to 2011 from five process-based land surface models: CLM4.5, LPJG, OCN,
334 ORCHIDEE, and VEGAS (see model list in Supplementary Table 2). All models were run
335 based on the TRENDY inter-comparison protocol during the period 1901-2010 using the same
336 observed climate drivers from CRU-NCEP Version 4
337 (<http://dods.extra.cea.fr/data/p529viov/cruncep/>), rising atmospheric CO₂ from the combination
338 of ice core records and atmospheric observations, and land use change from the Hyde database
339 (<http://dgvn.ceh.ac.uk/node/21>). NPP and GPP from all the five models were all resampled
340 into 1°×1° grids.

341

342 **The vector of change.** The vector of change in a certain variable takes both velocity and
343 direction into consideration. For each pixel, the velocity was defined as the ratio between the

344 30-year temporal trend and the spatial gradient in 30-year means^{4,6,9,51}. Temporal trend was
345 calculated using least squares linear regression for each grid⁵¹. Spatial gradient was calculated
346 using a 3×3 grid cell neighborhood based on the average maximum technique⁹. Following
347 Loarie *et al.*⁹, to convert cell height in latitudinal degrees to km, we used 111.325 km degree⁻¹.
348 To convert cell width in longitudinal degrees to km, we calculated $\cos\left(\frac{\pi}{180}y\right)111.325$, in
349 which y is the latitude of the pixel in degrees. We also added a uniformly distributed random
350 noise to each pixel to decrease the incidence of flat spatial gradients that cause infinite velocity
351 values⁹. For temperature, a random noise from -0.05 to 0.05 °C was used; for NDVI_{GS} and the
352 maximum NDVI value during growing season (MOS), a random noise from -0.005 to 0.005
353 was used; for the start / end of the growing season (SOS / EOS), a random noise from -0.05-
354 0.05 DOY was used; for NPP / GPP, a random noise from -0.5-0.5 gC m⁻¹ yr⁻¹ was used. The
355 direction of each vector was determined from the orientation of the spatial gradient, together
356 with the direction of change in a particular variable⁴. For example, if temperature showed a
357 positive trend during the study period, then the direction of temperature vector is towards areas
358 that used to be cooler. Therefore, assuming a south-to-north decrease in temperature over the
359 study area, then a northward (that is, along the spatial gradient) temperature vector indicates a
360 warming temperature during the study period. Similarly, a northward NDVI_{GS} vector refers to
361 an increase in NDVI_{GS} during the study period. A northward SOS vector is evidence for an
362 earlier trend in SOS date, while for EOS, a northward vector is evidence for a delayed EOS
363 date during the study period. A northward MOS vector is associated with a positive trend of
364 MOS at the local pixel during the study period.

365

366 We compared the velocity of change in NDVI_{GS} derived from GIMMS NDVI_{3g} with the one
367 obtained from MODIS NDVI during 2001-2011. The processing of MODIS NDVI datasets is
368 based on spectral bands that are specifically designed for vegetation monitoring and take state-

369 of-the-art navigation, atmospheric correction, reduced geometric distortions and improved
370 radiometric sensitivity into consideration⁴⁶. MODIS NDVI is considered to be an improvement
371 over the NDVI product derived from the AVHRR sensors^{46,52}, but it also has the disadvantage
372 of shorter time span compared to GIMMS NDVI_{3g}. Generally, the NDVI_{GS} velocity from
373 MODIS NDVI shows similar spatial pattern to that from GIMMS NDVI_{3g}, even though larger
374 values of the former than the latter in parts of central, northern and northeastern Canada
375 (Supplementary Figure 15).

376

377 **Analysis.** This study covered regions where vegetation productivity was temporally
378 significantly ($p < 0.1$) correlated with temperature from 1982 to 2011. Assuming a linear
379 relationship between vegetation productivity and temperature, the strength (correlation) of the
380 linkage between the two variables was determined by the Pearson correlation coefficient
381 between the time series of NDVI_{GS} and GS mean temperature, i.e., between the time series of
382 the sum of monthly NDVI during April-October and the mean temperature during April-
383 October. To compare the vectors of vegetation productivity and temperature velocities, for each
384 grid cell, we calculated the ratio between the velocity of vegetation productivity (V_V) along the
385 spatial gradient of temperature (V_V') and the velocity of temperature (V_T). Here V_V' was
386 computed as the velocity of the vegetation vector after projecting it along the spatial gradient
387 of temperature, which can be expressed as $V_V' = |V_V| \times \cos(|A_T - A_V|)$, where A_T and A_V is the
388 vector angle (in radians) for metrics of temperature and vegetation productivity, respectively.
389 The sign of the ratio between V_V' and V_T was determined from the directions of both vectors.
390 For a given pixel, a positive ratio is observed if the vector of change in vegetation productivity
391 displays the same direction as the vector of temperature change, suggesting that change in the
392 spatial pattern of vegetation productivity was directionally consistent with that of temperature.
393 A negative ratio indicates that the directional change in the spatial patterns of the two variables

394 were of opposite directions. The NDVI_{GS} vector was compared with the vector of GS mean
395 temperature with different definitions of GS: April to October, May to September, and April to
396 September. Comparisons of vector of NDVI_{GS} and that of mean annual temperature were also
397 presented. Since the timing of vegetation phenology is associated with temperature of the
398 preceding 0-3 months^{36,53}, here the vector of change in the SOS and EOS date were compared
399 with that of change in mean temperature during March to May and August to October,
400 respectively. The vector of change of MOS was compared with that of change in mean
401 temperature during June to July. Note that since it has been well recognized that increasing
402 spring temperature (i.e. positive trend of temperature) tends to result in an earlier SOS date (i.e.
403 negative trend of SOS date) over most of northern ecosystems during the past three decades⁵⁴,
404 regions where the change in vegetation productivity were consistent with warming trend refer
405 to those with a negative trend in SOS date during the study period. The vectors of change in
406 satellite-derived NPP, as well as model-simulated annual NPP and GPP were calculated using
407 the same methods as calculating NDVI_{GS} vectors, and compared with the vector of change in
408 GS (April to October) mean temperature.

409

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531

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536

537 **Author contributions**

538 S.L.P. designed research; M.T.H. performed analysis; and all authors contributed to the
539 interpretation of the results and the writing of the paper.

540

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546

547 **Figure Legends**

548 **Figure 1 | The velocity of vegetation productivity (NDVI_{GS}) and temperature (T_{GS}) from**
549 **1982 to 2011 over northern high latitudes (north of 50°N). a,** The spatial pattern of the
550 velocity of the vector of change in NDVI_{GS}. **b,** The spatial pattern of the velocity of the vector
551 of change in T_{GS}. **c,** The spatial pattern of the direction of the vector of change in NDVI_{GS}. **d,**
552 The spatial pattern of the direction of the vector of change in T_{GS}. **e,** The comparison between
553 velocity of NDVI_{GS} vector after projecting along the spatial gradient of T_{GS} and the velocity of
554 T_{GS} vector (see Methods). The growing season is defined as from April to October. The velocity
555 was calculated as the ratio between the 30-year temporal trend and the spatial gradient in 30-
556 year means (see Methods). The velocities shown in panel **a** and **b** are original velocities without
557 projecting the NDVI_{GS} vectors along the temperature gradient. For panel **c** and **d**, ‘N’, ‘NE’,
558 ‘E’, ‘ES’, ‘S’, ‘SW’, ‘W’ and ‘NW’ in the legend refer to ‘North-ward’, ‘Northeast-ward’,
559 ‘East-ward’, ‘Southeast-ward’, ‘South-ward’, ‘Southwest-ward’, ‘West-ward’, and ‘Northwest-
560 ward’, respectively. For panel **e**, the ratio between the velocity of NDVI_{GS} along the spatial
561 gradient of T_{GS} and the velocity of T_{GS} was calculated after projecting NDVI_{GS} vector along the
562 spatial gradient of T_{GS} for each pixel (see Methods). A blue color (positive ratio) suggests that
563 change in the spatial pattern of NDVI_{GS} was directionally consistent with the direction of
564 change in the spatial pattern of T_{GS}, while a red color (negative ratio) indicates that the former
565 was inconsistent with the direction of the latter. Note that only gridded pixels covered by natural
566 vegetation (defined following the International Geosphere-Biosphere Program based on a
567 MODIS land cover classification; Supplementary Figure 2) with annual mean NDVI value
568 larger than 0.1 are shown here.

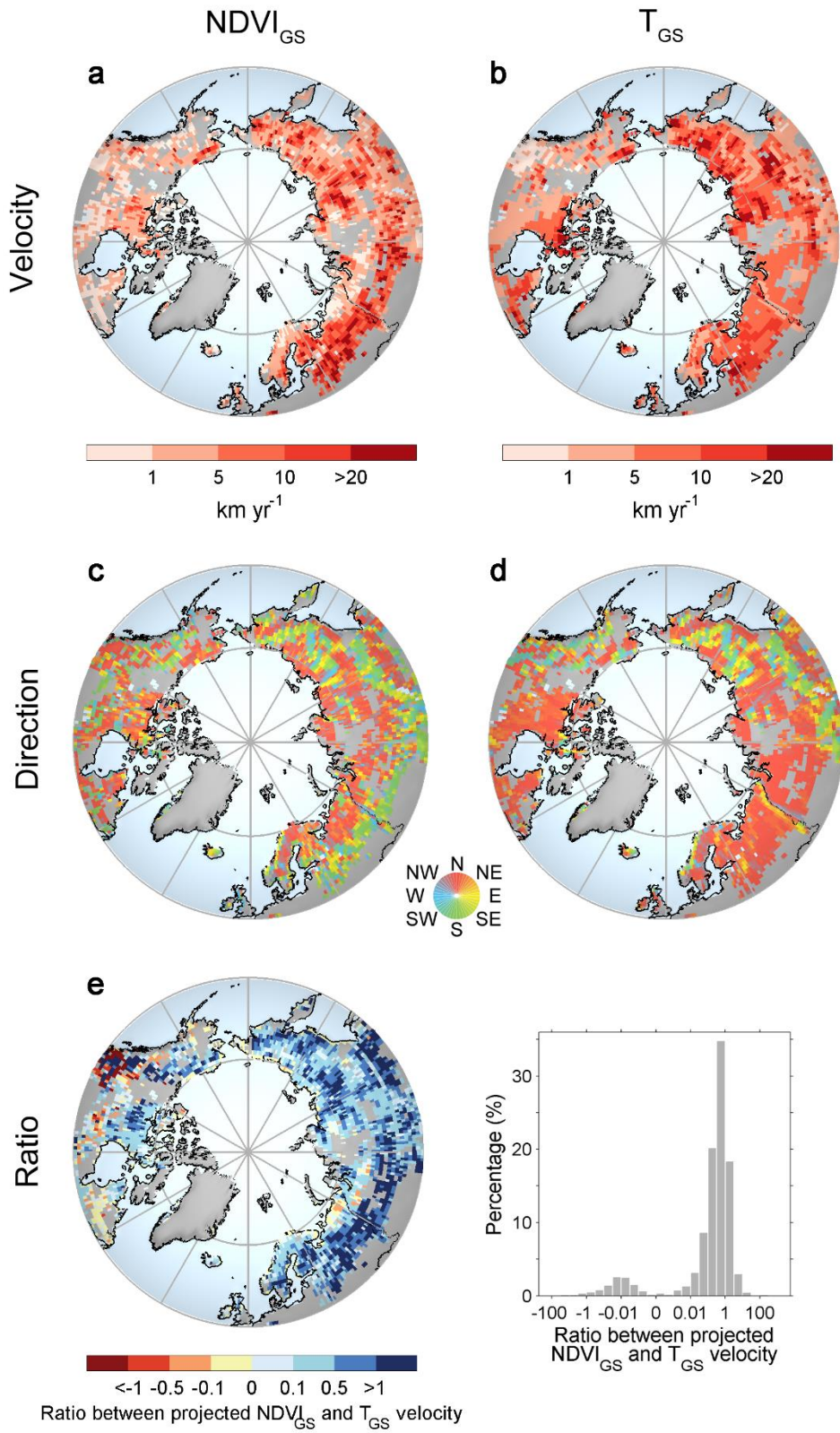
569

570 **Figure 2 | The velocity (a-c) and direction (d-f) of the vector of change in vegetation**
571 **phenology and physiology over the northern high latitudes (north of 50 °N) from 1982 to**

572 **2011 and comparison with the velocity of corresponding temperature metrics (g-i).**

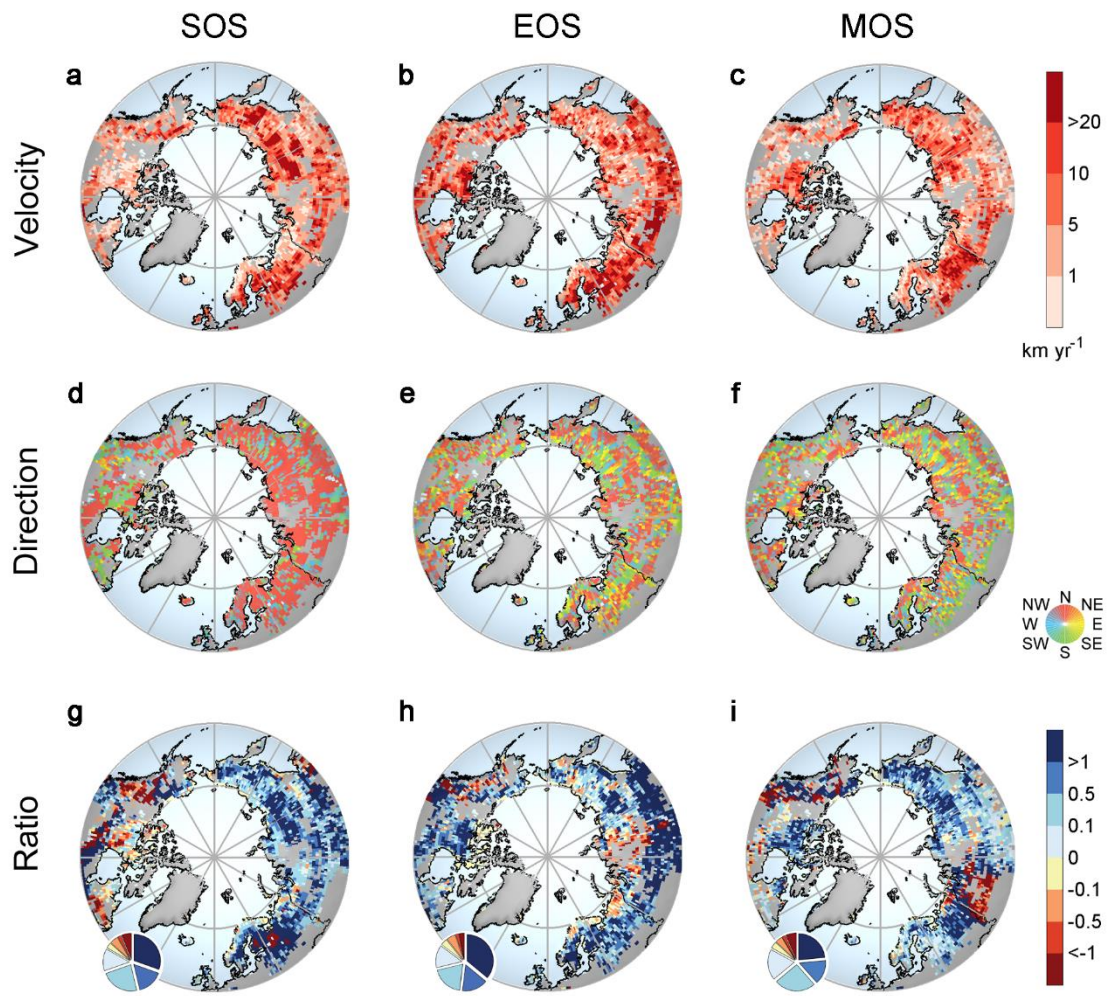
573 Vegetation phenology is characterized by the start of the growing season (SOS) and end of the
574 growing season (EOS); vegetation physiology is characterized by the maximum NDVI of
575 growing season (MOS). For each pixel, the velocity for a certain variable was calculated as the
576 ratio between the 30-year temporal trend and the spatial gradient in 30-year means for each
577 index (see Methods). The velocities shown in panel **a-c** are original velocities without
578 projecting the vegetation vectors along the temperature gradient. ‘N’, ‘NE’, ‘E’, ‘ES’, ‘S’, ‘SW’,
579 ‘W’ and ‘NW’ in the legend for panel **d-f** refer to ‘North-ward’, ‘Northeast-ward’, ‘East-ward’,
580 ‘Southeast-ward’, ‘South-ward’, ‘Southwest-ward’, ‘West-ward’, and ‘Northwest-ward’,
581 respectively. For panel **g-i**, the ratio between the velocity of SOS/EOS/MOS along the spatial
582 gradient of temperature and the velocity of temperature change was calculated after projecting
583 the vectors of change in SOS/EOS/MOS along the spatial gradient of corresponding
584 temperature metric for each pixel (see Methods). A blue color (positive ratio) suggests that
585 change in the spatial pattern of SOS/EOS/MOS was directionally consistent with the direction
586 of change in the spatial pattern of corresponding temperature metric, while a red color (negative
587 ratio) indicates that the former was inconsistent with the direction of the latter. Pie chart of
588 ratios shown in the spatial patterns is shown in the inset at bottom-left of panel **g-i**. Note that
589 only gridded pixels covered by natural vegetation (defined following the International
590 Geosphere-Biosphere Program based on a MODIS land cover classification; Supplementary
591 Figure 2) with annual mean NDVI value larger than 0.1 are shown here.

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