Corrigendum: Satellite observations of high northern latitude vegetation productivity changes between 1982 and 2008: ecological variability and regional differences

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Due to an error in our implementation of the Vogelsang test (Vogelsang 1998), the criterion used to determine where trends in remotely sensed gross productivity (Prs) were deemed deterministic at $\alpha = 0.05$ was overly lenient. This resulted in an overestimation of the total geographical area exhibiting deterministic Prs trends at $\alpha = 0.05$. This error affected figures 2, 3, 4 and 5 but does not modify any of the conclusions drawn from the analysis.

Corrected versions of the figures are included below.

In addition, but unrelated, titles of the panels in figure 3 were inadvertently omitted. They are included here.

Figure 2. Trends in remotely sensed gross productivity (Prs) between 1982 and 2008. Gray shading indicates the trend was non-deterministic based on a Vogelsang test ($\alpha = 0.05$ in the top panel and $\alpha = 0.1$ in the bottom panel). Areas in white were excluded from the analysis, as described in the text.
Figure 3. Areal fraction of the non-anthropogenic vegetated landscape displaying statistically significant deterministic changes in remotely sensed gross productivity (Prs, with bold lines representing $\alpha = 0.05$, and thinner lines representing $\alpha = 0.1$) when considering progressively longer time series since 1982. Tundra and boreal biomes were outlined using FAO (2001). (a) Tundra in North America. (b) Tundra in Eurasia. (c) Boreal forest in North America and (d) boreal forest in Eurasia.

Figure 4. MODIS tree cover in areas with and without statistically significant deterministic trends ($\alpha = 0.05$ in the top panel and $\alpha = 0.1$ in the bottom panel) in Prs between 1982 and 2008 in North American and Siberian tundra and boreal areas (as defined by a global eco-floristic zone map (see text for sources). Kruskal–Wallis tests showed statistically significant differences ($p < 0.001$) in tree cover between areas with positive and negative Prs trends in both North American and Eurasia.
Figure 5. Proportion of area in boreal Alaska showing decreases or increases in remotely sensed gross productivity (Prs), or no deterministic trend in productivity (α = 0.05 in the top panel and α = 0.1 in the bottom panel) over the period 1982–2008 along a gradient from evergreen to deciduous tree dominance, as mapped by (Beck et al 2011a). The deciduous fraction ranges from 0%, which represents purely evergreen stands, to 100%, which represents purely deciduous stands.

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In the first paragraph of the section ‘2. Data sets and methods’, the Normalized Difference Vegetation Index (NDVI) data set used was incorrectly referred to as GIMMS-NDVI version 3G with a $0.084^\circ$ spatial resolution. This should be corrected to GIMMS-NDVI version G with a $0.07^\circ$ spatial resolution.

Accordingly, the acknowledgement should state ‘We would like to thank ... Jim Tucker and Jorge Pinzon for providing the GIMMS version G data’, instead of ‘We would like to thank ... Jorge Pinzon for providing the GIMMS 3G data’.
Satellite observations of high northern latitude vegetation productivity changes between 1982 and 2008: ecological variability and regional differences

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Abstract
To assess ongoing changes in high latitude vegetation productivity we compared spatiotemporal patterns in remotely sensed vegetation productivity in the tundra and boreal zones of North America and Eurasia. We compared the long-term GIMMS (Global Inventory Modeling and Mapping Studies) NDVI (Normalized Difference Vegetation Index) to the more recent and advanced MODIS (Moderate Resolution Imaging Spectroradiometer) NDVI data set, and mapped circumpolar trends in a gross productivity metric derived from the former. We then analyzed how temporal changes in productivity differed along an evergreen–deciduous gradient in boreal Alaska, along a shrub cover gradient in Arctic Alaska, and during succession after fire in boreal North America and northern Eurasia. We find that the earlier reported contrast between trends of increasing tundra and decreasing boreal forest productivity has amplified in recent years, particularly in North America. Decreases in boreal forest productivity are most prominent in areas of denser tree cover and, particularly in Alaska, evergreen forest stands. On the North Slope of Alaska, however, increases in tundra productivity do not appear restricted to areas of higher shrub cover, which suggests enhanced productivity across functional vegetation types. Differences in the recovery of post-disturbance vegetation productivity between North America and Eurasia are described using burn chronosequences, and the potential factors driving regional differences are discussed.

Keywords: NDVI, GIMMS, MODIS, Arctic tundra, boreal forest, fire, shrubs, greening, browning

1. Introduction
Ongoing and projected acceleration of climate change at high latitudes is impacting a broad range of ecosystem processes, with multi-faceted implications for the regional carbon balance (Hinzman et al 2005, Soja et al 2007, Groisman and Soja 2009). Understanding these changes is important because they will feed back to climate directly through their effects on atmospheric CO₂ concentrations, and also indirectly by altering terrestrial energy budgets and hydrologic cycles (Chapin et al 2008, Wookey et al 2009). Changes in environmental conditions associated with warming, such as a lengthening of the growing season, have been directly linked to changes in vegetation productivity and composition (Angert et al 2005, Goetz et al 2005). For example, changes in shrub cover have been documented in situ in recent decades in tundra areas (Tape et al 2006). Increased shrub cover on the tundra may alter nutrient cycling (Shaver and Chapin 1991, Sturm et al 2005b), hydrology (Sturm et al 2001), trophic interactions (Joly et al 2007, Tape et al 2010), and permafrost dynamics.
(Sturm et al 2005b). If widespread, a shift toward a greater dominance of shrubs might affect the carbon balance (Shaver et al 1992, Mack et al 2004) and radiation budget (Chapin et al 2005, Sturm et al 2005a, Loranty et al 2011) of the tundra biome, amongst others through shifts in fire activity (Higuera et al 2008).

In the boreal forest biome fire is currently the dominant disturbance agent and exerts strong controls on the carbon balance (Bond-Lamberty et al 2007, Kasischke et al 2010, Beck et al 2011a, Turetsky et al 2011). Fire is also associated with broad shifts in vegetation composition and has been linked with historical evergreen tree establishment in Alaska (Lynch et al 2003, Johnstone et al 2010a). Fire frequency and severity have increased with recent climate warming in boreal North America (Gillett et al 2004, Kasischke and Turetsky 2006) and Siberia (Groisman et al 2007, Soja et al 2007). Alaskan boreal forests contain evergreen conifers, which dominate older stands in particular, as well as deciduous broadleaf trees which can dominate specific topographical positions and areas recovering from fire disturbance (Chapin et al 2006, Mack et al 2008). Moreover, areas exposed to severe burning show increased deciduous cover for decades after fire (Johnstone et al 2010b, Beck et al 2011a, Barrett et al 2011). In addition to altering the regional carbon balance, a transition from evergreen-dominated to deciduous forest, or vice versa, would substantially alter albedo and evapotranspiration (Bala et al 2007, Bonan 2008, Shuman et al 2011) as well as profoundly alter ecological communities (Werner et al 2006, Macdonald and Fenniak 2007, Wannebo-Nilsen et al 2010). These examples illustrate the need for a comprehensive examination of the magnitude and direction of changes in primary productivity across the northern high latitudes as a result of altered ecosystem processes associated with climate warming. This is particularly true in the case of the biophysical implications of climate change such as land-atmosphere feedbacks associated with shifts in energy and carbon balance (McGuire et al 2009, Wookey et al 2009, Euskirchen et al 2010). Satellite observations have provided unique insights into global primary productivity patterns and changes therein. Remotely sensed proxies of productivity (Prs), revealed widespread increases in above ground primary production associated with climate warming at high latitudes in the mid 1990s (Myneni et al 1997). A decade later, divergent responses in Prs were discovered between boreal and tundra biomes across North America (Goetz et al 2005) and the circumpolar region (Bunn and Goetz 2006, Piao et al 2011). Increases in Prs in high latitudes have been attributed to a release of cold temperature constraints on photosynthesis (Angert et al 2005), whereas decreases in Prs, or so-called ‘browning’ trends, have been linked to drought stress associated with higher vapor pressure deficits during summer (Bunn et al 2005, Lotsch et al 2005, Verbyla 2008). Field measurements since the 1990s support these interpretations, showing increases in shrub growth in Alaskan tundra (Tape et al 2006), and historically low growth rates in black and white spruce trees in Alaskan boreal forests (Barber et al 2000, Beck et al 2011c).

A refined interpretation of mapped changes in Prs, and ultimately the attribution of trends and patterns to particular ecological process are needed (McGuire et al 2009). The role of different vegetation functional types differentially driving the changes in Prs observed at coarse spatial resolution is largely unknown, other than the broad biome differences previously noted. Such attribution is essential to determine whether there are links between local observations such as tundra shrub expansion and Arctic-wide remotely sensed observations. Similarly, attribution of trends in Prs to particular functional types is needed to forecast changes in more complex ecological processes associated with changes in productivity. At the same time the attribution of observed trends to different climatic and non- or indirect climatic drivers such as disturbance is needed to estimate biophysical implications of changes in Prs, including energy budgets and carbon storage in vegetation and soils (Chapin et al 2000, Randerson et al 2006). In general however, assessing and linking Prs dynamics with the process that might be driving them is hampered by the discrepancy in spatial resolution between in situ measurements and long-term systematic satellite data records, which are generally on the order of hundreds of meters (Beck et al 2007).

Here we assessed differences in Prs changes since 1982 between regions and vegetation functional groups. We compared the high latitudes of Eurasia, where forests are dominated by larch (Larix sibirica and L. gmelinii), a deciduous conifer, and North America, where forests are dominated by evergreen conifer species. In Alaska’s boreal forest, we analyzed trends in Prs along a gradient of deciduous to evergreen forest cover. On Alaska’s North Slope, i.e. north of the Brooks Range and the largest expanse of tundra in the USA, we summarized changes in summer NDVI along a gradient of shrub cover to determine to which degree vegetation functional types exhibit differential responses to climate warming. Finally, we compared regional differences in Prs responses to fire in boreal regions of North America and Siberia, to further dissect regional differences in productivity trends.

2. Data sets and methods

Advanced very high resolution radiometer (AVHRR) measurements provide the longest record of continuous global satellite measurements sensitive to live green vegetation. To create a consistent data set from these measurements for global change research, the global inventory modeling and mapping studies (GIMMS) creates global maps of normalized difference vegetation index (NDVI) at 0.084’ spatial resolution and with twice-monthly frequency (GIMMS-NDVI version 3G, Tucker et al 2005). Because the GIMMS record starts in July 1981 and is well documented, it is most frequently used to assess long-term change in global and regional terrestrial vegetation productivity.

To validate the interannual NDVI signal in the GIMMS data set, trends in summer NDVI (July–August) over high latitudes of North America were compared to NDVI measurements from the moderate resolution imaging spectroradiometer (MODIS) aboard the Terra satellite launched in 1999. These monthly MODIS NDVI data (MOD13A3, Huete et al 2002) have a 1000 m spatial resolution and are of higher radiometric
and geometric quality than the GIMMS data. They were filtered to retain only data of the highest quality, based on the quality assessment flags provided with the MOD13A3 data. For the comparison, temporal linear trends in average yearly summer NDVI for the MODIS-GIMMS overlap period (2001–8) were calculated along with their associated uncertainty using ordinary least squares regression.

We estimated trends in PRs across northern latitudes over progressively longer periods of 21–27 years since 1982, and calculated the aerial fraction of positively and negatively trending areas in the 7 nested time series. Temporal patterns in these fractions were then compared in North America versus Eurasia, and in tundra versus boreal biomes to reveal any regional differences in recent productivity shifts. Tundra was delimited as the ‘polar’ class, and the boreal biome as the ‘boreal coniferous forest’, ‘boreal tundra woodland’, and ‘boreal mountain system’ classes mapped by the Food and Agriculture Organization of the United Nations (FAO 2001).

Prior to estimating trends in PRs, we applied a spatial filter to limit the analysis to areas dominated by non-anthropogenic vegetation cover as mapped in the International Geosphere–Biosphere Programme (IGBP) classification of 0.0042° (~1 km) MODIS reflectance data (MOD12Q1, Friedl et al 2002). The spatial filter is designed to exclude areas dominated by man-made land cover but it allows up to 60% of non-vegetated cover within a GIMMS grid cell, as non-vegetated areas have invariant NDVI. In practice, the filters excluded GIMMS grid cells where more than 40% was classified as non-vegetated (IGBP 0, 15–16) or where vegetated land cover was not at least three times larger than anthropogenic land cover (IGBP 12–14). To map trends in PRs over the 21–27 year periods, first the growing season length (GSL) was estimated for each GIMMS grid cell \( p \). The GSL was defined as two thirds of the period between the latest ‘start of greening’ date and the earliest ‘start of dormancy’ recorded between 2001 and 2004 in the MODIS Land Cover Dynamics product (MOD12Q2, Zhang et al 2006, Beck et al 2011c). For every year \( y \), PRs were then calculated in each grid cell \( p \) as the highest mean NDVI observed in the 24 NDVI values over a period of length GSL

\[
\text{PRs}_{p,y} = \max \left( \frac{\sum_{i=1}^{GSL-1} NDVI_{p,y,i}}{GSL-1} \right)
\]

where \( t = 0, 1, 2, \ldots, 24 - \text{GSL} \).

This moving window approach to estimating gross productivity is robust to changes in the timing of the growing season, but will not capture changes in its length if they are uncorrelated with changes in summer productivity. To detect deterministic, i.e. non-stochastic, trends in PRs we applied the Vogelsang test (Vogelsang 1998) to each time series with statistical significance set at \( \alpha = 0.05 \). The test prevents autocorrelation in the series, or abrupt disturbance events, from generating artificial trends (Goetz et al 2005).

2.1. Attribution of the trends

To discern how productivity responses differ between high latitude land cover types, tree cover, as mapped by Hansen et al (2003) using MODIS data, was compared between areas of no, positive or negative trends in PRs over the 1982–2008 period. In Alaskan boreal forest, we further assessed whether evergreen and deciduous vegetation dominance differentially influenced the observed changes in PRs by summarizing trends along a gradient of evergreen to deciduous vegetation cover using a MODIS-derived map of forest composition produced and described by Beck et al (2011a). Areas that had burned since 1982, as delineated in a database of Alaskan fire perimeters produced by the Bureau of Land Management, Alaska Fire Service (AFS, http://agdc.usgs.gov/data/blm/fire), were identified and excluded from the analysis.

To investigate the extent to which positive trends in tundra productivity were attributable to increased shrub growth, we tested on the North Slope of Alaska if summer (July and August) NDVI trends were more pronounced in areas of greater shrub density. Thus, yearly summer NDVI was summarized along the gradient of shrub cover present on Alaska’s North Slope which was recently mapped as a percentage of the surface and at 30 m resolution (described in more detail by Beck et al (2011b)). Summer NDVI was used because the MOD12Q2 phenology data and the derived PRs maps have gaps on the North Slope of Alaska and because the July–August period represents the growing season well in this region.

The GIMMS-NDVI time series was also used to describe and compare vegetation recovery after fire in North America and Siberia. A circumpolar data base of yearly burned area was compiled at GIMMS resolution using (a) the Alaska fire perimeter data set (1950–2007, http://agdc.usgs.gov/data/blm/fire); (b) the Canadian National Fire Data Base (NFDB, 1950–2007, acquired from the Fire Research Group at the Canadian Forest Service); (c) a gridded 500 m MODIS-derived monthly burned area product of Siberia for the period 2000–9 (MCD45A1, http://modis-fire.umd.edu/Burned_Area_Products.html), as well as two AVHRR-derived 1 km fire disturbance data sets: a first one used for 1996–9 (Sukhinin et al 2004) and a second one used for 1992–3 covering only central Siberia (George et al 2006). These regional fire data sets were resampled to express the yearly area burned in each GIMMS grid cell in both regions and combined with the GIMMS PRs time series to create a chronosequence (set of different aged burned areas) describing mean regional PRs as function of time since fire disturbance in boreal forests (FAO 2001). Grid cells were considered burned when >75% of their area was covered by a burn scar to ensure that the PRs time series of included areas was dominated by the effects of disturbance and recovery.

3. Productivity changes between 1982 and 2008

Trends in summer NDVI generated from the AVHRR series of satellites as well as the MODIS NDVI series agree well over their period of coincidence across the high latitudes of North America (figure 1). Areas where trends in GIMMS and MODIS summer NDVI contradict each other are few and generally have poor statistical support for a linear trend in summer NDVI in either data set. The only exception to that
en an area in northernmost Canada where vegetation cover is very sparse, and at a latitude where low illumination angles hamper the retrieval of consistent reflectance data from remote sensing (Shuai et al. 2008). This area was excluded from further analysis (figure 2).

As the GIMMS record grows in length, larger areas across North America show statistically significant Prs trends (figures 3(a) and (c)). Strikingly, statistical support is growing for the earlier reported contrast between trends in Prs in the tundra and the boreal biome of North America (Goetz et al. 2005), with ‘greening’ and ‘browning’ trends increasingly dominating the tundra and boreal biomes respectively. In contrast, the proportion of the Siberian tundra and boreal landscape that shows a deterministic trend in Prs, has remained relatively constant (figures 3(b) and (d)). Nonetheless, an increasingly negative forest Prs response is discernable in Siberia (figure 3(d)), although it is much less widespread than in North America. Indeed, in the Eurasian boreal biome Prs increases are still about twice as common as Prs decreases. Lower tree cover in parts of the Siberian boreal zone might be partly responsible for this; the FAO (2001) vegetation class ‘boreal tundra woodland’ had just 15 [SD = 14] per cent tree cover in Eurasia versus 29 [SD = 16] per cent in North America (tree cover differences between the two continents for the polar zone, boreal coniferous forest, and boreal mountain system were 6, −4, and 4%, respectively). As such, this zone of sparse tree cover, which occurs south of the tundra in Siberia and is here included in the boreal biome, is actually a transition zone from tundra to more densely forested areas. However, the boreal tundra woodland class represent only 14% of boreal Eurasia and productivity increases are more often observed in areas of high tree cover in Eurasia than in North America (figure 4). Extensive increases in Prs are observed in central and eastern Siberia suggesting environmentally driven productivity shifts. In contrast, some of the spatially scattered increases observed in western Siberia might be due to limitations in the land cover map used to mask agricultural landscapes, combined with forest recovery after agricultural land abandonment around the end of the Soviet era (de Beurs et al. 2009).

4. Boreal forests

In general, we observe a similar pattern of Prs responses with regard to tree cover in North America and Siberia.
Figure 3. Aerial fraction of the non-anthropogenic vegetated landscape displaying statistically significant deterministic changes in remotely sensed gross productivity (Prs) when considering progressively longer time series since 1982. Tundra and boreal biomes were outlined using FAO (2001).

Figure 4. MODIS tree cover in areas with and without statistically significant trends in Prs between 1982 and 2008 in North American and Siberian tundra and boreal areas as defined by a global eco-floristic zone map (see text for sources). Kruskal–Wallis tests showed statistically significant differences ($p < 0.001$) in tree cover between areas with positive and negative Prs trends in both North America and Eurasia.

Arctic tundra and areas at the tundra-forest ecotone, which are characterized by low tree cover, tend to show increasing Prs, whereas decreases in Prs are associated with the more densely forested areas (figure 4), which is consistent with earlier findings (Bunn and Goetz 2006, Beck et al 2011c). The increase in Prs at the forest-tundra ecotone is expected as the bioclimatic envelope for tree growth moves pole-ward, and is in line with observed expansion of larch and tall shrubs at treeline in Siberia and Alaska, respectively (Silapaswan et al 2001, Lloyd et al 2003). Areas of increasing and decreasing Prs differ less in tree cover in Eurasia than in North America, due to the widespread greening response observed in Central and Western Siberia. This area is unique in the sense that it is underlain by continuous permafrost and yet forested, and it roughly coincides with the range of Dahurian Larch (Larix gmelinii) (Osawa et al 2010). Lloyd et al (2011) found that trends in NDVI in the floodplains of this area reflect the prevalence of positive and negative responses of tree growth to climate warming. Moreover, they noted that evergreen tree species of pine and spruce, which have a more southerly distribution than larch, colonize larch dominated areas in central Siberia (Kharuk et al 2008).

Model projections for the 21st century predict that under scenarios of moderate warming ($<2^\circ C$) the limited depth of permafrost thaw and a positive larch-permafrost feedback could prevent the substitution of larch forests with evergreen needle-leaf trees (Tchebakova et al 2009, Shuman et al 2011, Zhang et al 2011). However, beyond this warming threshold larch forest resilience declines and transition to evergreen functional types would persist. Regardless, forest-steppe and steppe ecosystems are projected to expand northwards into the current southern extent of the Siberian forest (Vygodskaya et al 2007, Tchebakova et al 2009). If the pattern observed in Siberia is associated with a shift toward a greater cover of evergreen species in taiga forests, it would have profound implications for the exchange of carbon and energy between the land surface and the atmosphere (Bonan 2008). Further analysis of primary productivity responses along temperature and forest composition gradients in Eurasia will contribute to assessing and anticipating these projections, but might be constrained by our understanding of permafrost dynamics and change.
The presence of evergreen and deciduous tree functional types across North America’s boreal forest has not yet been assessed in relation to the observed patterns of Prs decline (browning). A recent comparison of changes in Prs and white aspen growth trends captured in tree-rings revealed positive correlation between the two observational data records, confirming that Prs trends in boreal Alaska accurately reflect decreased spruce productivity caused by climate warming (Beck et al. 2011c). In line with these observations, we observe expansion of ‘browning’ in areas dominated by spruce in this region (for areas not recently disturbed by fire) (figure 5). In other words, declining spruce productivity appears to be the major driver of the downward Prs trend in Alaskan boreal forest. Nonetheless, decreasing Prs is observed in areas that are largely dominated by deciduous trees as well, albeit much less frequently. Multi-year eddy covariance measurements show that drought induces decreases in primary productivity in both deciduous and evergreen–deciduous forests (Welp et al. 2007) and that net carbon exchange in well-drained deciduous ecosystems is particularly drought sensitive (Grant et al. 2009). Additional in situ observations of growth in these deciduous boreal trees, including tree ring analyses, are needed to understand their response to climate change of recent decades and how they might fare in the future. The latter question is particularly pertinent if continued climate warming in the coming decades increases spruce mortality, and associated shifts in the fire regime limit spruce forest regeneration (Johnstone and Chapin 2006, Beck et al. 2011c). As a consequence, the suitability of future environmental conditions for currently non-dominant boreal species, such as deciduous trees in North America, and northward migrating temperate species across the boreal biome will determine the rate and extent of any future biome shift (Lucht et al. 2006).

5. Arctic tundra and shrubs

Tundra areas well north of tree line in both North America and northern Eurasia continue to display increased productivity, which in North America has become more pervasive in the last decade (figure 2). This phenomenon has been repeatedly discussed in the context of increased shrub growth (Jia et al. 2003, Walker et al. 2003, Bunn et al. 2005, Goetz et al. 2005, Bunn and Goetz 2006) following documented shrub expansion over the last half century through repeat photography (Sturm et al. 2001, Tape et al. 2006). More recent comparisons of shrub growth rings and summer NDVI time series in Siberia indicate significant correlation in some shrub species (Forbes et al. 2010), but not in others (Blok et al. 2011). Experimental research further shows that deciduous shrubs (i.e. dwarf birch, alder and willow species) respond to multi-year warming with increased growth, but this response is shared with other functional types, particularly graminoid species (Walker et al. 2006).

A summary of summer NDVI time series along a shrub cover gradient on the North Slope of Alaska indicates that the remotely sensed ‘greening’ trend is not unique to shrub-dominated areas (figure 6). Although shrubs are completely absent from relatively few areas on the North Slope of Alaska (Beck et al. 2011b), this observation indicates that the Prs trends in tundra areas are not the result of changes in productivity of shrub vegetation alone, but rather a response shared by multiple functional types of vegetation in this biome. The latter was also suggested by earlier reports of high consistency in the temporal trends in annual peak NDVI across three temperature zones (Jia et al. 2003). This result implies significant changes in Arctic terrestrial ecosystems can be expected irrespective of shrub presence, a finding also recently noted with respect to albedo changes (Loranty et al. 2011).
6. The influence of fire disturbance

In burned forests of boreal North America, NDVI recovered to pre-burn levels within 5–10 years (figure 7(a)) which is comparable to earlier estimates of NDVI-recovery times following fire (Hicke et al 2003, Goetz et al 2006). NDVI increases following fire persisted for 15–20 years, however, and exceeded pre-burn levels between 20 and 40 years after the fire. This rebound in productivity is consistent with peak productivity in intermediate-aged boreal forest succession, as well as with eddy covariance estimates of gross primary production along a chronosequence of burned boreal forest sites (Goulden et al 2011). In Alaska this intermediate-aged productivity peak has been related to greater cover of deciduous trees (Johnstone et al 2004, Beck et al 2011a, Alexander et al 0000).

A much less consistent influence of fire disturbance on the NDVI chronosequence is visible in northern Eurasia (figure 7(a)). This is partly due to the more limited Eurasian fire databases providing a smaller sample size (figure 7(b)), despite the larger extent of the northern Eurasian boreal domain (taiga). Nonetheless, there is a much less pronounced post-disturbance Prs drop in Eurasia relative to North America, which may reflect differences in tree mortality, the density of tree cover, or both. Similarly, a recovery signal is not evident in the time series, confirming observations in central Siberia by Cuevas-González et al (2009) showing MODIS Siberia NDVI had not returned to pre-burn levels after 13 years of post-fire vegetation recovery. Unfortunately, we cannot rule out the possibility that these patterns are artifacts of a high prevalence of false positives in the Eurasian fire databases.

A shift in dominant tree species during succession, common in North America, generally does not occur in Siberian larch forests—rather biomass recovery depends primarily on regrowth of larch trees (Zyryanova et al 2010). However, very low recruitment in burn scars has been reported in Siberian larch forests when a thick moss and duff layer remains after burning (Sofronov and Volokitina 2009). Furthermore, Siberian larch lack fire-resistant seed cones, thus recruitment depends on masting events and is highly variable between years. Together, the variation in post-fire soil conditions and seed availability generate large variability in forest regeneration in the larch dominated portion of boreal Siberia. We note, however, that the variable degree of human management in many of the burned areas in Eurasia, as well as the potential occurrence of other forms of disturbance than fire (Krankina et al 2004), emphasize the need for further research into these post-disturbance recovery dynamics.

7. Conclusions

Earlier reported contrasts between productivity trends in Arctic tundra and boreal forest biomes have amplified between 2002 and 2008. In tundra areas, consistent greening trends are continuing in both North America and Eurasia. In North America, the proportion of tundra areas increasing in productivity has steadily grown since 1982, reaching 32% of non-barren areas in 2008. This greening trend appears unrelated to shrub density, indicating that primary productivity is increasing across a range of functional vegetation types. Boreal forest areas in both North America and Eurasia increasingly show declining Prs, the so-called ‘browning’ phenomenon that has been tied to increasing drought stress.

Areas displaying decreasing productivity tend to have denser forest cover, although some areas of high tree cover in Eurasia do show increasing productivity. In Alaska, productivity decreases are most prevalent in areas dominated by coniferous trees. They are observed in areas with relatively high broadleaf deciduous tree cover as well, albeit less frequently, warranting further research into the health and productivity of these less widespread forest types. In boreal North America, broadleaf deciduous trees and shrubs are also often prominent in vegetation succession after fire and their biomass accumulation most likely contributes to the recovery of NDVI values after fire. The absence of a shift in dominant tree species post-fire and a wide range of larch recruitment conditions emerge as a potential causes for a less distinct NDVI-recovery pattern across boreal forests of northern Eurasia.
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