

EDITORIAL COMMENTARY

Arctic browning: extreme events and trends reversing arctic greening

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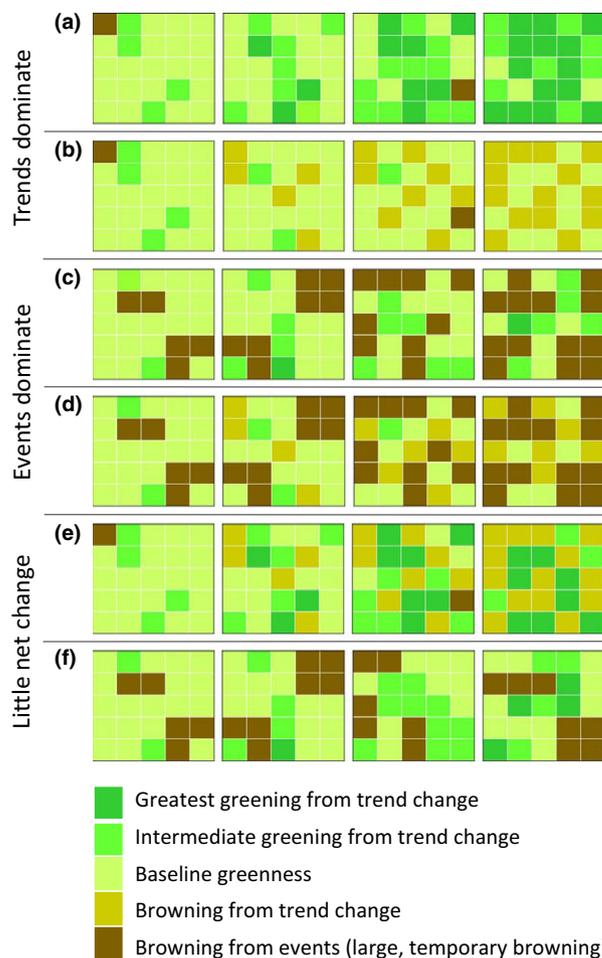
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NOAA's recent assessment of Arctic greenness has reported a remarkable finding: the Arctic is browning (Epstein *et al.*, 2015). Whilst a clear greening trend has been apparent for most of the satellite record's 33 year history (indicating an increase in biomass and productivity), there is now an overall decline in greenness from 2011 to 2014. If this is a new direction of travel for arctic vegetation, rather than just a temporary departure from long-term greening, this has major implications for not only our understanding of the future of arctic vegetation, but also arctic carbon, nutrient and water cycling, surface energy balance and permafrost degradation, and therefore feedback to climate, all of which are strongly influenced by vegetation composition, productivity and biomass. The urgency in understanding what is happening here is clear. Most models predict arctic greening; to what extent are they wrong, and why?

Arctic greening has rightly received much attention. Satellite and observational data have consistently confirmed an increase in vegetation cover and productivity in many regions (Xu *et al.*, 2013) caused most notably by the expansion of large stature deciduous shrubs (Myers-Smith *et al.*, 2015). Likewise, field simulation experiments provide strong evidence that greening is driven by warming (Elmendorf *et al.*, 2012). However, the magnitude of the recent browning is large and can-

not be ignored. For both the Eurasian Arctic and the Arctic as a whole, Epstein *et al.* report the 2014 maxNDVI (greenness) to be below the 33-year average. To find lower values than 2014, you have to go back to 1996 for the whole Arctic and to 1993 for the Eurasian Arctic. However, while browning is the overall trend, there is considerable regional variation and the Arctic is not browning everywhere. These findings raise important questions that represent priority challenges, including (1) what is driving the browning? (2) is browning the new trajectory or only a temporary reversal of greening? and (3) what arctic regions and vegeta-

Fig. 1 Scenarios for arctic browning and greening with trend and event drivers. Boxes represent a landscape unit or region (e.g. edge size of magnitude 10–100 km) with each 'pixel' a vegetation or landscape unit within it. Each subsequent box moves on 10 years (allowing recovery from browning events). Scenarios where trends dominate: (a) trend greening; (b) browning driven by trend climate (e.g. reductions in summer warmth index/increased snow cover duration). Scenarios where events dominate: (c) browning from spatially and temporally discreet events combine to result in net browning – in this scenario, against a background of trend greening in nondamaged areas; (d) max browning – spatially and temporally discreet events add to trend browning. Scenarios where little or no net change occurs despite drivers operating: (e) trend greening and trend browning largely balanced; (f) trend greening and event browning largely balanced.



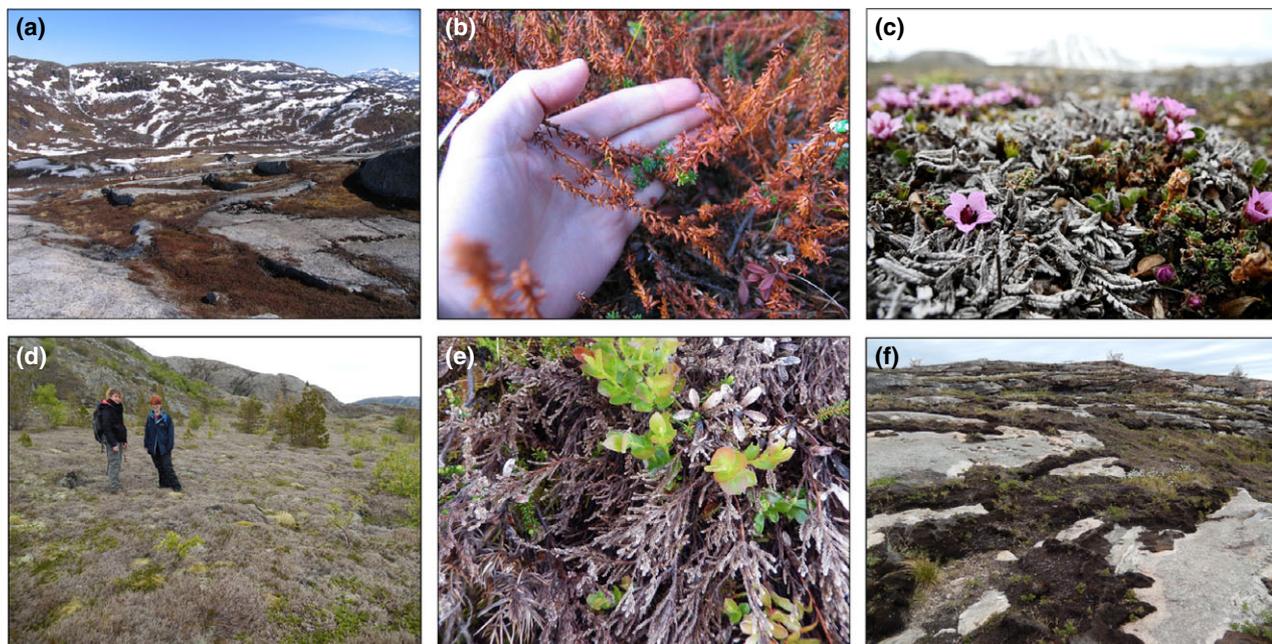


Fig. 2 Browning events: (a, b) extreme winter warming damage to *Empetrum nigrum* heathland in Sub-Arctic north-west Scandinavia; (c) icing damage to *Dryas octopetala* in High Arctic Svalbard (*Saxifraga oppositifolia* flowering); (d, e) frost drought damage to *Calluna vulgaris* heathland in central Norway; and (f) fire on flammable, frost drought killed, *Calluna* heathland resulting in soil exposure and erosion. Photo credits: (a, b) Stef Bokhorst, (c) Rachael Treharne, (d, e, f) Gareth Phoenix.

tion types are most sensitive so might show the greatest browning in future?

Browning can be caused by a reversal of greening drivers. As raised by Epstein *et al.* (2015), declines in greenness in some regions, especially early season, arise from greater and longer snow cover (Bieniek *et al.*, 2015), and an earlier analysis showed the declining greening of the Eurasian arctic to be linked to reduced summer warmth index (Bhatt *et al.*, 2013). If so, against an ongoing trend of some of the greatest warming on the planet and declining snow cover duration (AMAP, 2011), we might expect greening to resume soon, although a warmer arctic will result in some areas receiving more snow and having longer snow cover duration (AMAP, 2011). Equally, changes in the 'trend' drivers of greening may not explain the widespread extent of browning, and other mechanisms will apply.

In particular, while warmer growing seasons (i.e. trend climate change) may be the dominant driver for greening, a number of lines of recent evidence show that extreme events and winter warming drive browning. Critically, both extreme events and winter temperatures are also increasing as part of climate change, and in the case of winter temperatures, increasing much more so than summer (AMAP, 2011). So, despite having the greatest rates of warming globally, the concurrent increases in browning drivers that come with climate change means that we can be far

less certain about ongoing greening (example browning and greening scenarios are shown in Fig. 1). For instance, tundra fire can cause complete loss of vegetative cover, and tundra fire frequency is expected to increase with climate change (Bret-Harte *et al.*, 2013). Thermokarst development with permafrost degradation can lead to browning where thaw features expose ground or create water bodies (although succession will re-green these). In the record-low productivity for north-west Scandinavia observed in 2012, 14 different types of anomalous weather events were detected that drove browning (Bjerke *et al.*, 2014). While these occurred further south than the study area of Epstein *et al.*, they may well represent an early warning for higher latitudes as they warm. The best studied of these is currently extreme winter warming which leads to mid-winter bud burst and loss of freeze tolerance (Bokhorst *et al.*, 2011), although the numerous other drivers identified range from warm autumns reducing winter hardening, rain-on-snow resulting in plant ice encasement, lack of snow cover combined with high irradiance leading to frost drought (Fig. 2), through to snow falling on unfrozen ground enhancing snow mould growth and respiratory losses from subnivean plants. In addition, outbreaks of defoliating insects and rust fungi were also cited as browning drivers. Furthermore, events can interact to drive greater browning, such as frost

drought damaged heathland becoming more fire prone (Fig. 2f). However, while this may suggest the Arctic faces an onslaught of browning, vegetation also shows evidence of rapid recovery from these events (vegetation in the extreme winter warming and fire studies recovered in 2–4 years; Bokhorst *et al.*, 2011; Bret-Harte *et al.*, 2013).

And here lays one of the main challenges. Events are hard to study (and those that occur in winter even more so). The sporadic nature of events in time and space means they cannot be predicted beforehand, infrastructure cannot be set up in advance in the right place and time to monitor an upcoming event, and when they do occur, it may be the aftermath of damage that allows us to detect the event, hence missing the opportunity to study it in progress. The damage is also often transient, with ecosystems recovering after a few years. So, while greening may be viewed more as a steady and gradual process, browning may come from a large number of different drivers, either as trend change but also often as biotic or weather events, reducing greenness in different parts of the landscape, at different times, temporarily. Net browning will arise if the sum of these in space and time overrides greening. Predicting that from a large number of events that we still poorly understand is a real challenge.

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