Wildland fires delay Arctic snow cover formation

Wildland fires in snow-dominated regions such as the Arctic can have profound effects on snowpack characteristics. Satellite observations reveal a delay in snow cover formation in the Arctic following major wildland fires. Machine learning and causal analyses suggest that this delay is linked to fire-induced reductions in albedo and increases in surface temperature.

The question

Multiple lines of evidence suggest that anthropogenic warming is driving shifts in snowpack dynamics, leading to either earlier snowmelt or later snow cover formation[1]. At the same time, wildland fires are becoming more frequent, larger and more intense — a trend expected to accelerate with continued climate warming[2]. Fires in high-latitude and snow-dominated areas such as the Arctic are concerning because they can have prolonged and profound effects on snowpack characteristics. Despite growing recognition of this issue, research on the response of snow cover to wildland fires remains limited. Furthermore, the underlying mechanisms linking summertime wildland fires to subsequent changes in snow cover are still poorly understood and require further investigation.

The discovery

Using long-term satellite observations from 1982 to 2018, we analysed trends in burned area and snow cover, as well as their interactions, across Arctic regions. Snow cover duration was found to increase with latitude, with the longest periods — exceeding 220 days — occurring within the Arctic Circle. By contrast, areas south of the Arctic Circle typically exhibited snow cover durations of less than 150 days. Over the study period, the average snow cover duration across the Arctic showed a decreasing trend ($P < 0.01$), shortening by more than 15 days, with a particularly sharp decline over the past two decades. Concurrently, satellite-based estimates of the burned area from the FireCCILT11 dataset revealed widespread and intensifying fire activity across the Arctic, characterized by a notable increase in burned area (more than 2 Mha) over time.

To examine the link between snow cover formation and pre-snow season wildland fires, we used XGBoost machine learning models to predict annual delays in snow cover formation based on various climatic variables. Our analysis indicated that post-fire albedo, air temperature and land surface temperature are the most influential predictors (Fig. 1a–c). In addition, causal inference using structural equation modelling[3] and convergent cross mapping revealed a robust causal pathway: larger burned areas lead to decreased post-fire albedo and increased post-fire land surface temperature, which in turn increases post-fire air temperature (Fig. 1d). This rise in air temperature ultimately contributes to delayed snow cover formation. Overall, our findings suggest that as wildland fire activity expands, the resulting post-fire warming increasingly contributes to delays in snowpack development across affected regions.

We also examined the regional response of snow cover phenology, specifically the timing of its formation and disappearance, to major wildland fires across the Arctic. Our analysis revealed a delay ($P < 0.05$) in snow cover formation during the years following large fire events. The most substantial delay, exceeding 5 days relative to the 3-year pre-fire average, was observed in the snow season immediately after a fire. In addition, we found a generally positive correlation between the timing of snow cover formation and the extent of burned areas, indicating that larger fire-affected regions tend to experience proportionally later snow accumulation. Together, these findings suggest that wildland fires in the Arctic partly contribute to delayed snow cover formation in a warming climate, with the degree of delay intensifying with fire severity.

Future directions

The effects of wildland fires on snow cover are variable across regions and shaped by complex ecological interactions[4]. In forested areas, vegetation has a dual role. Trees can intercept snowfall, and once burned, might allow more snow to reach the ground. Additionally, forest canopies influence wind-driven snow redistribution. Thus, fire-induced forest loss can accelerate or delay snow disappearance, depending on site-specific factors such as topography and wind exposure[5]. These dynamics underscore the pivotal role of forest structure in regulating snow cover responses to fire. To better understand these interactions, future research should explore the fire–forest–snow nexus in greater detail, with particular attention to identifying the key factors that drive snowpack variability across diverse Arctic environments.

Delayed snow cover formation in response to wildland fires is an increasingly urgent issue. As climate change intensifies fire activity and snow cover decline, understanding the interplay between these phenomena is crucial for predicting future impacts and informing effective management strategies. By elucidating the connection between diminished snow cover and the rising frequency of wildfires, ecosystems, communities and biodiversity can be better safeguarded from the consequences of a warming climate.

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EXPERT OPINION

"This paper attempts to address a critically important topic in climate change: how post-fire conditions affect snow cover. The authors use a machine learning approach to explore how relevant variables affect snow cover duration in the Arctic and discern that not only do climatic variables affect snow cover duration, but the burned area does as well." **Anne Nolin, University of Nevada, Reno, Reno, NV, USA.**

FIGURE

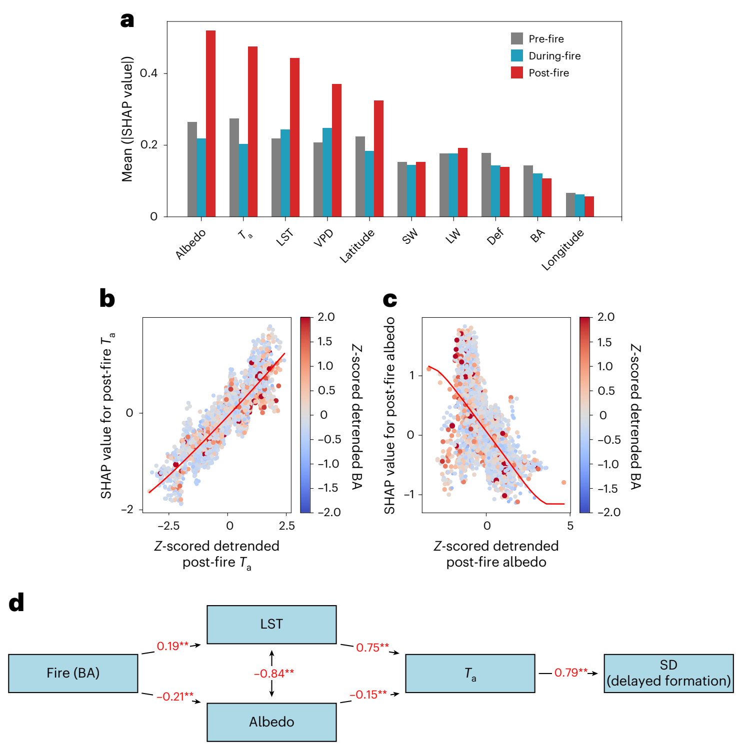

Fig. 1 | Drivers of delayed snow cover formation following fire events. a, Mean Shapley additive explanation (SHAP) values for various climatic variables (albedo, air temperature (T_a), land surface temperature (LST), vapour pressure deficit (VPD), surface downwelling shortwave flux (SW), surface downwelling longwave flux (LW) and climatic water deficit (Def)) during the pre-fire, during-fire and post-fire periods. Summertime burned area (BA), latitude and longitude included as static predictors. The SHAP values indicate the importance of the variables to the machine learning model's prediction. **b**,**c**, SHAP-dependence plots for post-fire T_a (**b**) and post-fire albedo (**c**) with colour indicating BA. Red lines indicate fitted trends. **d**, Structural equation model illustrating causal relationships between summertime fire, post-fire albedo, post-fire LST, post-fire T_a and start day of snow cover (SD). Standardized path coefficients are shown along arrows; significance is indicated (**$P < 0.01$). © 2025, Qing, Y. et al., CC BY-NC-ND 4.0.

BEHIND THE PAPER

This research was motivated by media reports highlighting increasingly severe wildfires and diminishing snow cover across North America in recent years. Although extensive literature links spring snow cover and melt timing to summertime fire regimes, less attention has been given to how fire activity influences the timing of snow cover formation. This knowledge gap inspired our investigation into the response of snow cover to wildfires, aiming to provide a more comprehensive understanding of the feedback mechanisms between fire regimes and snow dynamics in a warming climate.

The most challenging aspect of our work was establishing a convincing mechanistic explanation for the observed statistical patterns. With constructive feedback from collaborators and peer reviewers, we identified a robust causal pathway by which intensified wildfires delay the formation of snow cover. **S.W.**

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FROM THE EDITOR

"That wildfires can affect snow cover has been discussed for some regions, but few studies have given such a comprehensive assessment over larger scales." **Editorial Team, *Nature Climate Change*.**