CLIMATE CHANGE

From white to green: Snow cover loss and increased vegetation productivity in the European Alps

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Mountains are hotspots of biodiversity and ecosystem services, but they are warming about twice as fast as the global average. Climate change may reduce alpine snow cover and increase vegetation productivity, as in the Arctic. Here, we demonstrate that 77% of the European Alps above the tree line experienced greening (productivity gain) and <1% browning (productivity loss) over the past four decades. Snow cover declined significantly during this time, but in <10% of the area. These trends were only weakly correlated: Greening predominated in warmer areas, driven by climatic changes during summer, while snow cover recession peaked at colder temperatures, driven by precipitation changes. Greening could increase carbon sequestration, but this is unlikely to outweigh negative implications, including reduced albedo and water availability, thawing permafrost, and habitat loss.

Climate change is causing major changes in the physical environment, altering ecosystems and their services to humans (*1*). Receding glaciers are iconic symbols of climate change; snow cover loss is equally important but has received less attention. Snow cover loss has direct feedback effects on climate change (*2*) and affects downstream ecosystems and people, as mountain glaciers and snow provide half of the world's freshwater resources (*3*). Snow is also an important driver of ecosystem functions in mountains (*4*). Its seasonal and spatial patterns affect hydrological and biogeochemical processes, such as litter decomposition, carbon sequestration, nutrient availability, soil moisture, and surface water dynamics (*4*, *5*). Snow cover duration controls the life cycle of organisms by determining growing season length. Mountain topography creates uneven snow accumulations, resulting in a mosaic of microhabitats with different biotic assemblages that vary in phenology, morphology, and diversity (*6*).

Although precipitation is projected to increase in the European Alps, rapid warming in mountain regions is reducing the proportion of precipitation falling as snow, leading to predicted snow mass reductions of up to 25% over the next 10 to 30 years (*7*). So far, warming has been strongest in summer and spring, and snow depth has accordingly decreased most during spring and at lower elevations (*8*). However, temperatures may remain cool enough at high elevations to result in snow mass increases (*7*). Satellite-based studies have thus far detected no overall change in snow cover in the European Alps (*9*), presumably because of data limitations with regard to spatial resolution, temporal extent, and cloud cover (*10*).

Potential impacts of warming, precipitation changes, and snow cover loss on alpine vegetation are deducible from the Arctic, where productivity increases have resulted in the "greening of the Arctic" (*11*). Greening has indeed begun to be detected in the mountains of central Asia and the European Alps (*12*–*15*). It is generally driven by plant species growing faster and taller, and newly colonizing species cause further structural changes (*16*). This initiates a feedback loop, because taller species trap blowing snow and increase radiation exchanges, leading to altered snow patterns, faster snowmelt, and reduced snow cover (*17*, *18*). However, snow that is too shallow impairs vegetation through reduced thermal insulation and less meltwater availability during the growing season (*4*, *6*), which might be even more influential than warming itself as climatic extreme events such as droughts become more frequent with climate change (*16*, *19*). Indeed, decreased vegetation productivity has been observed in the Arctic ("Arctic browning") (*11*, *19*) and has already overruled greening trends in the mountains of central Asia (*14*).

In this study, we exploited remote sensing advances to analyze spatiotemporal trends of snow cover and vegetation productivity during the past 38 years (1984–2021) in the European Alps. We used all Landsat (satellites 4 to 8) images available in Google Earth Engine (*20*) for June to September at a resolution of 30 m, excluding areas below 1700 m, forests, and glaciers (fig. S1 and table S1) (*21*). Because long-term changes of vegetation productivity [measured as normalized difference vegetation index (NDVI)] and snow cover [measured as normalized difference snow index (NDSI)] are nonlinear (*22*), we applied individual nonparametric tests to the time series of each 30-m cell (*21*). We assessed the area and magnitude of changes in NDVI, snow cover duration within the growing season (June to September, hereafter "summer snow"), and presence of year-round snow cover; whether these changes were correlated; and how climatic changes (i.e., annual and summer temperature and precipitation) and topography (i.e., solar radiation and curvature) affected these trends.

Summer snow and year-round snow recession occurred in only 4 and 9% of the area, respectively, whereas increases were negligible (Fig. 1 and table S2). Overall, snow cover receded nonetheless, with stronger declines in summer snow than in year-round snow (mean Sen's slope of −0.002 and −0.001 per decade, respectively) (Fig. 2A and table S5). The pronounced snow depth reduction measured at meteorological stations (*8*) has therefore already resulted in snow cover recession that is detectable from space. If warming continues at predicted rates (*7*), more pronounced changes can be expected.

Greening occurred in 77% of the European Alps above the tree line, which is substantially more than previously reported (56%) (*15*). Contrary to trends in the Arctic and the mountains of central Asia (*11*, *14*, *19*), however, browning occurred only in <1% of the area (Fig. 1 and table S2). Short-term browning events may have occurred but, if so, were not yet frequent and/or intense enough to be detected in the long term (*22*). Productivity thus increased significantly and, with 0.026 NDVI units per decade (mean Sen's slope), considerably faster than in the mountains of central Asia or France (*12*, *14*).

Where snow cover changes occurred, a significantly larger area than expected by chance experienced decreases rather than increases (Fig. 1D and table S2), and the magnitude of change was significantly larger for snow cover than for NDVI. Year-round snow changed >20 times more than NDVI and twice as much as summer snow, whereas summer snow changed 9 times more than NDVI (Fig. 2B and table S6). One explanation is the different nature of the three variables. Satellites cannot measure snow depth, and snow can thus only be recorded as present or absent. Year-round snow is an annual binary variable, but the duration of summer snow can vary in magnitude, and NDVI is a continuous measure of productivity. However, the higher magnitudes of year-round snow decrease indicate abrupt losses in the wake of critical thresholds of environmental conditions, whereas NDVI seems to have increased irregularly over time.

Areas with decreases in year-round snow were more likely to have shorter-lasting summer snow (Pearson's correlation coefficient, *r*, of 0.44), but greening only coincided with

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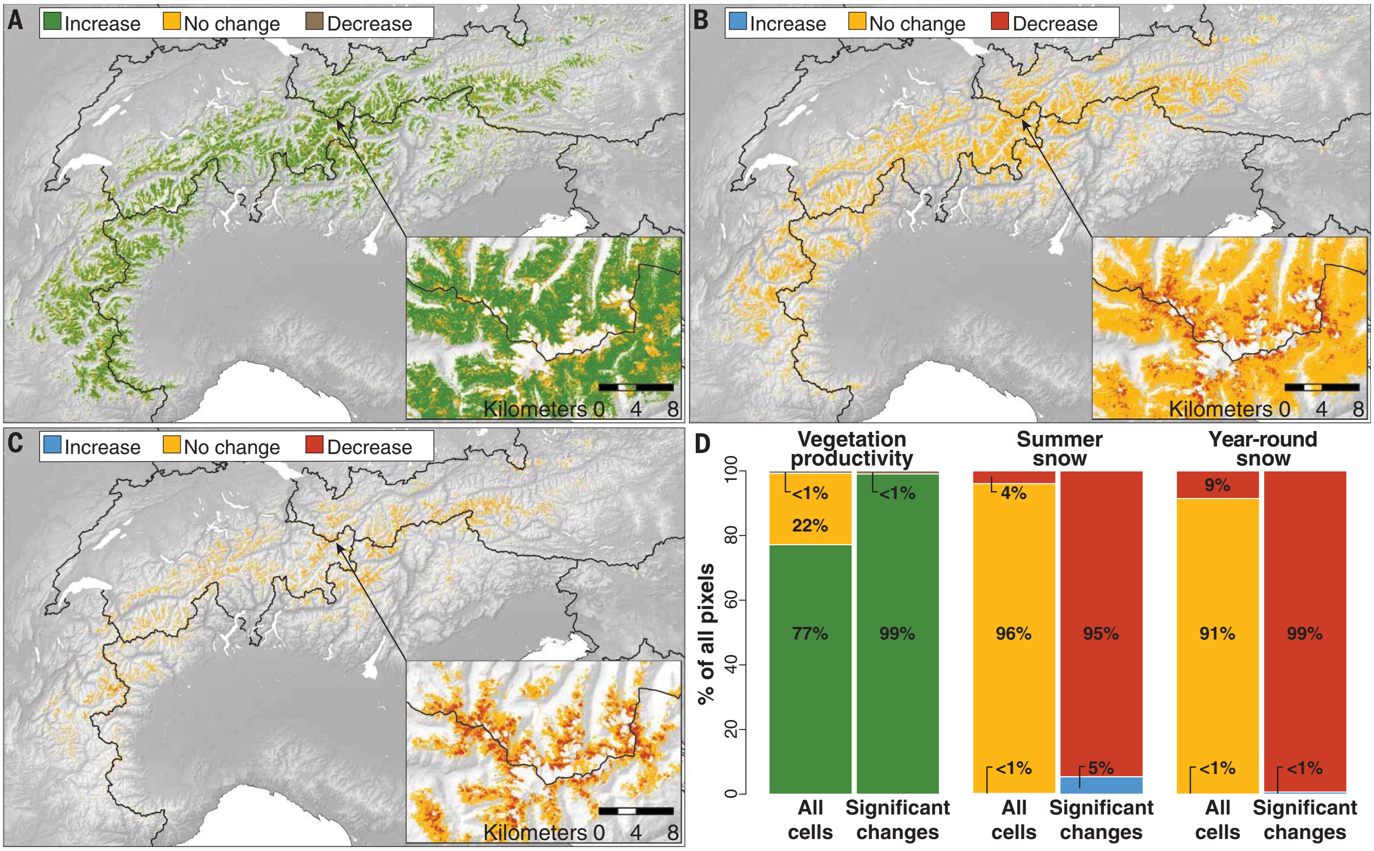

Fig. 1. Temporal changes of NDVI and snow cover in the European Alps from 1984 to 2021. Significant increases in (**A**) NDVI, (**B**) duration of summer snow, and (**C**) occurrence of year-round snow. Insets are examples of an Alpine region. (**D**) This panel depicts the proportion of these cells using the same colors as the maps. Temporal changes were calculated as Mann-Kendall's τ at a resolution of 30 m for nonforest and nonglaciated areas above 1700 m. See tables S3 and S4 for results based on Sen's slopes and linear regressions.

changes in summer snow and year-round snow in a fraction of the European Alps (Pearson's r of −0.08 and −0.06, respectively; see table S9 for correlations based only on cells with significant changes and table S10 for correlations based on linear regressions). Greening after snow cover reduction detectable from space might therefore take longer than the 38 years considered here.

Greening trends might simply occur at lower elevation than reductions in snow cover because both trends depend not only on climatic changes and topography but also on ambient temperatures (i.e., mean annual temperatures over the study period). For example, if temperatures increase by 2°C, this has less effect on snow in areas with low temperatures than in warmer areas where less precipitation falls as snow. Similarly, warming affects vegetation more once a critical threshold for plant growth is reached but induces water stress at higher temperatures (*6*), and NDVI can saturate in dense vegetation at low elevations (*23*). Indeed, most pronounced increases of NDVI occurred in areas around 0.5°C (~2300 m), while the magnitude of change for snow cover peaked around −5°C (~3000 m) (Fig. 3A). Notably, we could not detect any snow cover increase at low temperatures (i.e., high elevations), contrary to current predictions (*7*). While the importance of environmental drivers also varied with ambient temperatures, climatic changes were consistently more influential than topography (Fig. 3, B to D). Warming strongly affected NDVI, but in the subalpine and alpine zone (−2° to 2°C), where greening was most pronounced, changes in summer

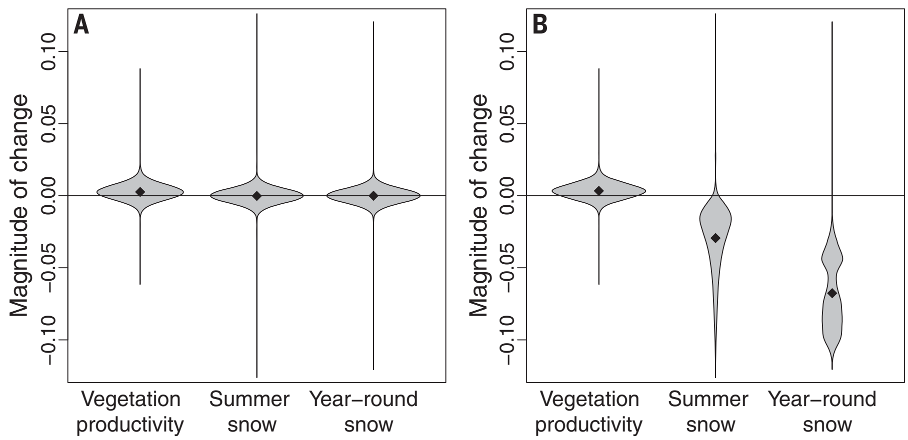

Fig. 2. Magnitude of temporal changes of vegetation productivity and snow cover in the European Alps from 1984 to 2021. Polygons represent magnitude of changes measured as Sen's slope in (**A**) all cells and in (**B**) only cells with significant changes. Diamonds depict intercept-only estimates. See tables S5 and S6 for model estimates and tables S7 and S8 for results based on linear regressions.

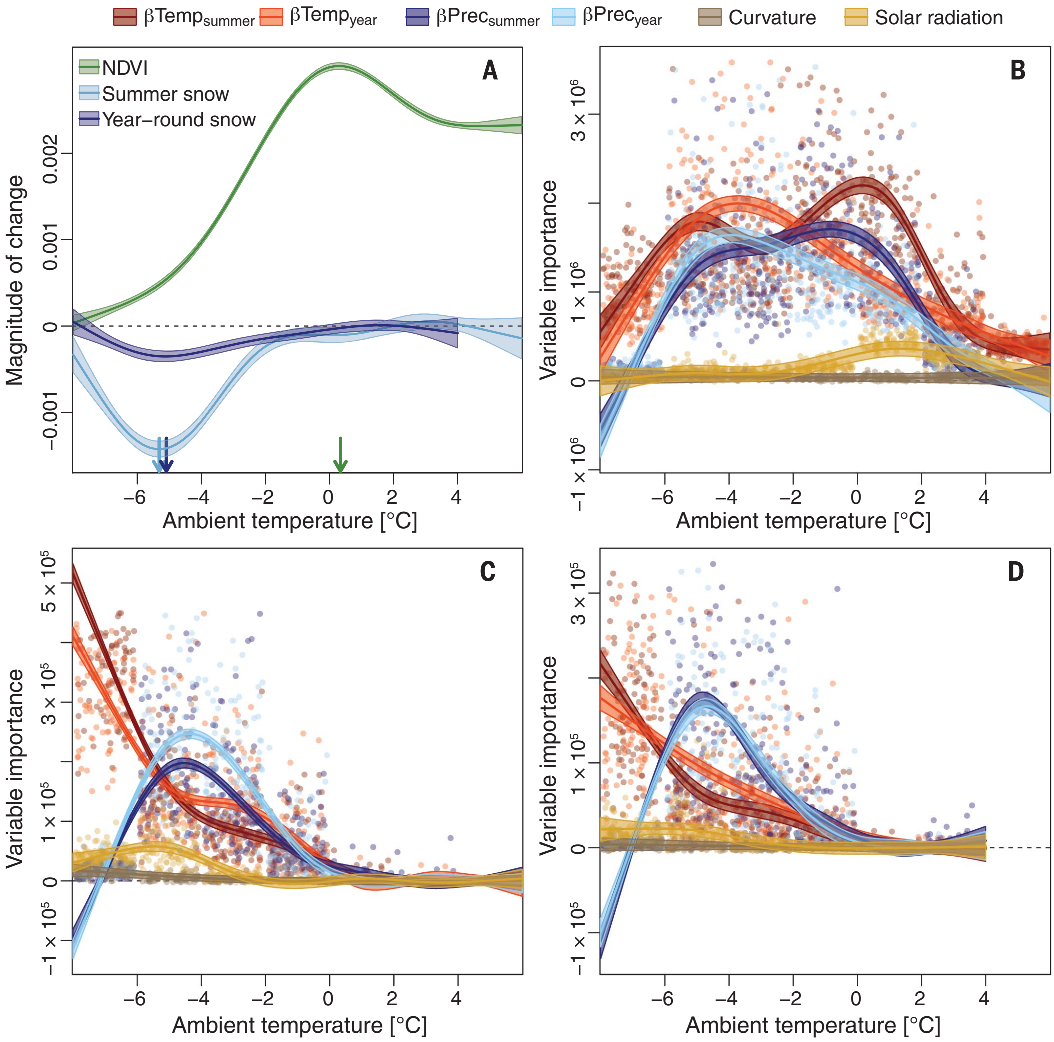

Fig. 3. Temporal changes and effect of environmental variables on NDVI and snow cover at varying ambient temperatures in the European Alps from 1984 to 2021. (**A**) Temporal changes of NDVI, snow persisting in summer, and year-round snow. Magnitudes of temporal changes are measured as Sen's slope and are negative for decreases and positive for increases. Colored arrows represent ambient temperatures (i.e., mean annual temperatures) at which the respective trend is peaking. Variable importance measured as mean squared error (MSE) increase for NDVI (**B**), summer snow (**C**), and year-round snow (**D**) was derived from 100 replicates of individual random forests with 10,000 trees on the basis of 10,000 cells for each bin of 2°C of ambient temperature. Higher values represent higher importance, whereas negative values suggest no importance. In all panels, zero is depicted as a black dashed line, and colored lines and shaded areas represent model fits and 0.95 confidence intervals, derived from generalized additive models with a *k* value of 6. Colored dots represent raw values of MSE increase of changes in summer temperatures ($\beta Temp_{summer}$), annual temperatures ($\beta Temp_{year}$), summer precipitation ($\beta Prec_{summer}$), and annual precipitation ($\beta Prec_{year}$), as well as curvature of the terrain (representing whether the topography parallel and perpendicular to the slope is convex, even, or concave) and annual solar radiation. See fig. S2 for temporal trends with varying smoothing parameters, figs. S3 to S5 for effects of environmental variables, and fig. S6 for results based on linear regressions.

temperature and summer precipitation were most influential (Fig. 3B). Warming was most influential for snow cover changes at the lowest temperatures, whereas precipitation changes were more important for maximal snow cover reductions (−6° to −2°C) (Fig. 3, C and D).

The European Alps are turning from white to green, albeit so far with stronger trends in greening than in snow cover loss. Yet the feedback loop between greening and snow recession implies that continued greening will cause earlier snowmelt (*17*, *18*, *24*), with important implications. Both greening and snow cover loss have direct consequences on the climate. Increasing plant productivity could have a dampening feedback on current climate change through the sequestration of atmospheric CO_2 (*25*). Compared with other biomes, however, plant productivity is low in mountains (*6*) and has likely only minor global effects. By contrast, receding snow cover and greening reinforce climate change by decreasing surface albedo (*2*, *24*). This is further amplified by thawing permafrost, which might release greenhouse gases (*26*) and additionally causes rockfalls and landslides in mountain environments (*27*). Overall, this reinforcement likely outweighs dampening effects (*25*). Lastly, greening results not only from increasing productivity of originally present plant species but also from compositional and functional changes of the vegetation (*11*) and its associated biota, and it may cause large-scale structural changes across the European Alps. Together with decreasing snow cover, this has profound impacts on water provision, economy, recreational activities, and landscape aesthetic value (*3*). Our results thus highlight that climate change has already had pronounced impacts on mountain environments detectable from space, and they reinforce concerns about further predicted changes (*7*).

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ACKNOWLEDGMENTS

We thank M. Chevalier for his support. **Funding:** This work was funded by Swiss National Science Foundation grant CR23I2_162754 (to A.G. and G.M.). M.L. acknowledges Academy of Finland funding (grant 342890). **Author contributions:** Conceptualization: C.C., A.G., G.M., and S.B.R. Formal analysis: S.B.R. Funding acquisition: A.G. and G.M. Investigation: M.G. and S.B.R. Methodology: A.G., G.M., and S.B.R. Software: O.B., M.G., and S.B.R. Visualization: S.B.R. Writing – original draft: S.B.R. Writing – review & editing: O.B., A.G., M.L., M.G., G.M., and S.B.R. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** Data and code are available on the online repository Zenodo (*28*).

SUPPLEMENTARY MATERIALS

science.org/doi/10.1126/science.abn6697
Materials and Methods
Figs. S1 to S6
Tables S1 to S10
References (*29*–*38*)
MDAR Reproducibility Checklist

Submitted 12 December 2021; accepted 3 May 2022
10.1126/science.abn6697

Science

From white to green: Snow cover loss and increased vegetation productivity in the European Alps

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Science, 376 (6597), • DOI: 10.1126/science.abn6697

Alpine snow loss and vegetation gain
Mountains are experiencing more dramatic warming than lower elevations, with increasing snowmelt and changing patterns of snowfall. Rumpf *et al*. examined how the past four decades of climate change have influenced snow cover and vegetation productivity in the European Alps. Using remote sensing data, they found that snow cover declined significantly, but so far over less than 10% of the study region. Vegetation productivity has increased across over two-thirds of the area above tree line, with potential ecological and climate impacts. Feedbacks between snow and vegetation will likely lead to even more pronounced changes in the future. —BEL