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Tis' the season to be freezin': Synthesizing the past 10 years of winter climate research spanning from genomes to watersheds at a high-elevation watershed.

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Winter is a critical season in snow-dominated ecosystems that connects microbe-soil-plant interactions to watershed functions. Mountain snowpacks are disappearing globally, and microbes, soils, and plant communities in these environments are likely to be adversely affected, yet the extent and impact on watershed functions remains uncertain. The East River watershed is a high-elevation system located in Upper Gunnison County, Colorado. Over the past 50 years, the maximum depth of snowpack has declined by about 7% per decade, leading to an earlier snowmelt date which now occurs up to 21 days earlier in the year. We have leveraged a range of observational studies, ecosystem-scale field manipulations, and modeling approaches throughout the past decade, with complementary measurements spanning from genomes to watersheds, to better understand the consequences of snowpack loss on watershed functions. At the molecular scale, microbial genomes reflect selection for physiological traits that are adaptive for growth during winter snowpack accumulation, during seasonal snowmelt, and after snowpack loss in spring. Snowmelt imparts successional shifts in the abundance and metabolic activity of distinct microbial groups that partition nitrogen substrate utilization in order to fuel snowmelt-associated microbial biomass blooms. Soil nitrogen pulses after snowmelt result from a collapse in the soil microbial population size, high metabolic activity of ammonia-oxidizing soil archaea, and host-specific infection by DNA and RNA bacteriophages. At the ecosystem scale, experimentally accelerating the date of snowmelt results in the rapid convergence of community composition of soil bacteria, fungal and herbaceous plants, leading to a decoupling of belowground and aboveground phenology. This asynchrony alters soil N cycling and the balance between ecosystem carbon uptake versus carbon loss. Collectively, these results inform our interpretations of predictions of future watershed scale N exports and improve our understanding of watershed functions as the extent and persistence of mountain snowpacks continue to decline.