The Effects of Snowmelt Timing and Warming on Plant Phenology
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INTRODUCTION
Phenology, the timing of plant activity, is crucial for maintaining balance in the relationships between organisms and their environment. For example, species mismatch in flowering time and pollinator efforts, could threaten plant reproduction (Cleland et al. 2007). A warming climate and earlier snowmelt often cause phenology to advance (Sherwood et al. 2017, Oberbauer et al. 2013, Khorsand Rosa et al. 2015). Using an experimental manipulation of both snowpack duration and temperature, we ask how the timing of leaf out, flowering, and senescence of Geum rossii, a common alpine species, tracks the environment. We predict that both warming and snowmelt may be advancing phenology of Geum rossii, and that these factors may be interacting with one another or acting independently.

METHODS
The data for this research was collected at Niwot Ridge in the Front Range of the Rocky Mountains of Colorado, USA (40.05°N, -105.59 °W) (See Fig. 3 below)

In the summer of 1993, a 60m long by 2.8m high snow fence was erected to create a gradient in snowmelt timing (See Fig. 1 above)

Several International Tundra Experiment (ITEX) chambers were deployed both behind and outside of the snowfence to create warmer conditions. Placed only in the summer months, these chambers increase warming by 2- 5°C (See Fig. 4 below)

Each warmed plot was paired with a non-warmed plot at late and early gradient points on the leeward side of the snowfence.

From 1993-1996, three phenological stages of Geum rossii were recorded: leaf out, flowering, and senescence

While phenology data was collected from 1993-1996, we focus on the final year (1996) after plots had been subjected to 3 years of treatment

Using the data collected in 1996 we conducted 2-way ANOVAs in R, version 4.0.1 (R Core Team, 2020)

To meet assumptions of normality, required by parametric statistical testing, we used a Box-Cox transformation on the leaf out data.

RESULTS
Earlier snowmelt advanced leaf out by around 35 days (Fig. 5, F(1,36) = 230.23, P < 0.001), there was no significant effect of warming.

Earlier snowmelt advanced flowering by around 28 days (Fig. 6, F(1,26) = 331.40, P < 0.001), there was no significant effect of warming.

Earlier snowmelt advanced senescence by around 11 days (Fig. 7, F(1,36) = 47.80, P < 0.001) and warming delayed senescence by about 5 days (Fig. 8, F(1,36) = 8.65, P = 0.006)

While both earlier snowmelt and warming affected senescence, there was no significant interaction between the two (F(1,36) = 2.37, P = 0.13)

DISCUSSION
In line with our prediction, we saw earlier leaf out, flowering and senescence of Geum rossii with earlier snowmelt timing.

In contrast to our predictions, however, temperature did not have a significant effect on leaf out or flowering, though it did delay timing of senescence.

This suggests that cooling fall temperatures drive Geum rossii senescence, while spring forcing temperatures do not seem to have a strong control on leafout and flowering. Instead, snowmelt timing seems to be a strong driver for the leaf out and flowering time of Geum rossii.

These findings align with previous studies which saw that earlier snowmelt timing was a stronger driver of phenological shifts than warming for several other alpine and arctic species (Khorsand Rosa et al. 2015 and Sherwood et al. 2017).

The effects of warming and snowmelt on phenology differ by plant species and the region in which each species is found (Sherwood et al. 2017, Oberbauer et al. 2013, Khorsand, Rosa et al. 2015) This added complexity makes untangling the direct causes of shifting phenology a complicated task.

Some species with advanced leaf out caused by earlier snowmelt are left susceptible to frost damage by spring frost events and also risk mismatch in timing of pollinator efforts. Both threats would ultimately lower reproductive abilities of a population leading to community shifts in these ecosystems (Sherwood et al. 2017).

There are also species that are able to adapt to these shifts and could out-compete less plastic species, again leading to a shift in population dynamics (Khorsand, Rosa et al. 2015).

Future work in phenology research could be focused on accounting for the abundance of plastic species in nature versus the abundance of non-plastic species, and cataloging the responses of each to better inform future conservation efforts.

REFERENCES
Cleland et al. (2007) "Warming plant phenology in response to global change". https://doi.org/10.1073/pnas.0611223104
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