Theory level citations

Background in why compound disturbances create novel conditions and trajectories:  
White, P.S. and Jentsch, A., 2001. The search for generality in studies of disturbance and ecosystem dynamics. In *Progress in botany* (pp. 399-450). Springer, Berlin, Heidelberg.

Paine, R.T., Tegner, M.J. and Johnson, E.A., 1998. Compounded perturbations yield ecological surprises. *Ecosystems*, *1*(6), pp.535-545.

Scheffer, M. and Carpenter, S.R., 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. *Trends in ecology & evolution*, *18*(12), pp.648-656.

Turner, M.G., 2010. Disturbance and landscape dynamics in a changing world. *Ecology*, *91*(10), pp.2833-2849.

Loss of ecological memory, “resilience debt.” Should be exacerbated with ongoing disturbances.  
Johnstone, J.F., Allen, C.D., Franklin, J.F., Frelich, L.E., Harvey, B.J., Higuera, P.E., Mack, M.C., Meentemeyer, R.K., Metz, M.R., Perry, G.L. and Schoennagel, T., 2016. Changing disturbance regimes, ecological memory, and forest resilience. *Frontiers in Ecology and the Environment*, *14*(7), pp.369-378.

Variability in extent and frequency is most important per numerical modeling:

Fraterrigo, J.M., Langille, A.B. and Rusak, J.A., 2020. Stochastic disturbance regimes alter patterns of ecosystem variability and recovery. *PloS one*, *15*(3), p.e0229927.

Expectations for changing feedbacks  
Buma, B., 2015. Disturbance interactions: characterization, prediction, and the potential for cascading effects. *Ecosphere*, *6*(4), pp.1-15.

Other:

Bond, W.J. and Parr, C.L., 2010. Beyond the forest edge: ecology, diversity and conservation of the grassy biomes. *Biological conservation*, *143*(10), pp.2395-2404.

Dantas, V.D.L., Hirota, M., Oliveira, R.S. and Pausas, J.G., 2016. Disturbance maintains alternative biome states. *Ecology Letters*, *19*(1), pp.12-19.

Westerling, A.L., Turner, M.G., Smithwick, E.A., Romme, W.H. and Ryan, M.G., 2011. Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. *Proceedings of the National Academy of Sciences*, *108*(32), pp.13165-13170.

Disturbances are a major driver of long-term ecosystem functioning, and in many ecosystems are the major force that creates and maintains ecosystems themselves (e.g., grassland vs. forests, Dantas et al. 2016). Theory suggests that in disturbance-adapted systems, ecosystems retain ecological memory via resilience mechanisms after even intense disturbances (Johnstone et al. 2016). However, if additional disturbance events occur within the timeframe of recovery those resilience mechanisms can be overwhelmed, creating “ecological surprises” (Paine et al. 1998), meaning recovery trajectories or alternate regimes that are not easily predictable from knowledge of the individual disturbance agents themselves (Scheffer and Carpenter 2003, Buma 2015). Theoretical modeling agrees, suggesting changes in disturbance frequency are more important than changes to intensity or other disturbance characteristics (Fraterrigo et al. 2020).

Research into the effects of disturbance frequency changes have almost exclusively focused on high intensity disturbances and single short-interval events (2 disturbances). Two major gaps remain. First, little empirical research has been conducted on the ongoing effects of short-interval events. While modeling studies suggest progressive loss in ecosystem functions (e.g., ongoing fires in Yellowstone, Westerling et al. 2011), it is also true that subsequent disturbances interact with previous disturbance conditions, changing intensity and overall impacts (Buma 2015). Trajectories inferred from single short-interval events may therefore not be valid if frequency of disturbances remains high.

Second, little research has been directed towards lower intensity disturbances. Disturbance severity is mediated by external factors, such as topography. Theoretically, this should lessen cumulative impacts (Paine et al. 1998), though if frequency is truly the most significant factor (Fraterrigo et al. 2020) then that moderation effect should disappear with ongoing events. This too has not been empirically investigated.

Here we test those theories directly in a disturbance adapted biome, by looking at 1-3 events in short succession across two topographic contexts known to mediate disturbance severity. If changes continue to accrue with a continued high frequency of disturbances, we should see divergence between each disturbance history; similarly, if frequency is the most important driver of ecosystem recovery, we should see resilience erode even in favored, historically more resilient/resistant to change topographic contexts.