Emma Steigerwald
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Invisible imprints of glacial melt

The frogs were dying. The streams were drying.

There in the Cordillera Vilcanota, a heavily glaciated mountain chain in southern Peru, Quechua tradition suggested that these events were linked: it is the frogs who call the rain when it is dry, and keep the streams flowing. Perhaps it was because of the perceived threat that disappearing frogs posed to their crops and pastures that local smallholders, despite their extreme geographic isolation, managed to broadcast their concerns widely. A long-term amphibian monitoring effort was soon established in the Cordillera. Almost immediately, scientists associated the reported die-offs with the pathogen that has driven the largest biodiversity loss in history: the chytrid fungus *Batrachochytrium dendrobatidis* (Bd). However, I am drawn to the Cordillera because I wonder if the dying frogs and drying streams are, ultimately, tightly linked. This spring I had my first season in the Cordillera to collect data for testing my hypotheses, supported by the Tinker Foundation Exploratory Grant for Field Research, by spirited local guide Gumercindo Crispin Condori, by dedicated Cusco undergraduate students Jared Guevara Casafranca and Peter Condori Ccarhuarupay, and by the ever-patient packhorses Chumpipaya, Muro, Oroscocha, Yanapaya, and Yura.

Figure 1. Gumercindo and packhorse Chumpipaya descend to Laguna Sibinacocha, at the south side of the Cordillera Vilcanota. Photo by E Steigerwald.

Drying streams are just one symptom of much larger changes occurring across this landscape. This season, as we crossed the landscape and spoke to smallholders who have lived here all of their lives, we were confronted by the local repercussions of a globally changing climate. We met herders and cultivators digging new irrigation ditches and diverting new springs, replacing streams that have ebbed or gone extinct. We easily crossed high mountain passes that just a few decades ago were blocked by glacial ice. At the foot of the mountains, our steps sunk sometimes over a foot into dessicated carpets of cushion plants, which though they had reached ages of several hundred years recently parched as their perennial water sources became

Figure 2. With Gumercindo and Peter in Osjollo Pass, the longest transmontane pass in the Cordillera Vilcanota. Photo by E. Steigerwald.

ephemeral. We walked through communities of plants and microbes, only a few years old, that have blossomed behind the tails of retreating glaciers. Three frog species have taken advantage of this new habitat, expanding their ranges 660 vertical feet upslope and setting the global elevational record for amphibians, at 17700ft: the Marbled four-eyed frog, Andean toad, and Marbled water frog. With nets and bags, we captured these colonists—colonists of narrow mountain passes, regularly blanketed in snow or hail, where solar UV is relatively unfiltered by the atmosphere and night covers the ponds in sheets of ice. Cracking pond ice with the butt of our tadpole nets, or digging under snow to flip rocks, we had daily cause to marvel at these intrepid amphibians.

Figure 3. We must take careful precautions in this fieldwork to not transmit Bd between frogs and sites, sterilizing equipment between animals and anything that has touched the ground before moving across the landscape. Here, a Marbled four-eyed frog peers over single-use nitrile gloves as he is measured, weighed, sexed, swabbed, and contributes a toe tip to science. Photo by E. Steigerwald.

I am exploring two mechanisms by which climate change driven range expansions might influence the disease dynamics of Bd, and thus die-offs, in frogs. Firstly, each time frogs colonize farther up the mountain passes, the colonists are not entirely representative of their source population. Instead, a small number of juveniles migrates forwards, representing an entirely random subset or sometimes individuals with traits enhancing their movement capability (ie strong back legs). In this way, each "founder event" reduces the biological variation present relative to the source population, including the genetic variation underlying frogs' physical traits. So when expansion occurs rapidly over a large distance, genetic variation may be lost simply by chance, rather than because it is not useful. Frogs' susceptibility to infection by the Bd pathogen can be influenced in several ways by their genetics. Studies have shown that a frog having specific versions of particular immune genes, or inheriting different versus identical versions of genes from each parent, can affect its Bd resilience. Therefore, I suspect that frogs on an expanding range front may be more susceptible to the Bd pathogen, both because variation conferring resilience may have been lost by chance, and because these frogs are more likely to inherit the same gene versions from both parents.

A second potential influence of climate change driven range expansions on disease dynamics concerns their effect on patterns of genetic exchange. Deglaciation opens new movement routes across the landscape by melting open mountain passes. The colonization of these passes may therefore allow for the interbreeding of groups of animals separated by the mountain barrier. For example, the final glacial "stopper" preventing movement across Osjollo Pass, the longest pass in the Cordillera, only melted in the late 1970s. Since the Cordillera has served as a 50-km long ice barrier across the landscape, perhaps for some five millennia, frogs colonizing its newly-melted mountain passes may now be interbreeding with frogs that they have accumulated genetic differences with over time. I am curious if this opportunity for new genetic exchange improves the Bd resilience of these frogs. If it has, I will resolve whether general "hybrid advantage" or specifically the effect of interbreeding on immune genes is responsible.

The Cordillera is a perfect example of a landscape that at times appears nearly pristine, while local flora and fauna is in fact silently dealing with compound anthropogenic pressures.

Dazzlingly turquoise waters tumble from its slopes. Miniature alpine plants coat the ground with their delicately intricate structures. Human population density is so low that you can walk non-stop for a week without seeing a fence or a person. Yet, beyond the control of residents, human and otherwise, meltwater streams are drying. Glaciers are melting. Some species are changing their distributions as conditions change, but each species in its own unique way, such that biological communities are changing. And a novel pathogen, that likely emerged in Asia and only spread this far with the amphibian pet trade, has swept across this entire landscape. The three frog species I am studying have used accelerated deglaciation as an ecological opportunity to expand into new upslope habitat. Considering them successful climate responders, we might be less concerned about their long-term persistence. However, in a context of compound pressures, what if "successful" response to one pressure moderates susceptibility to a second pressure, like disease?

The people of this region continue to dedicate themselves to the hard work and fickle rewards of cultivating tubers and raising alpaca. However, their anxiety over their changing landscape is absolutely palpable. Their future options are narrowing. When we explained that we were studying frogs, people emphasized that we could work with them only as long as we did not hurt or distress them—despite the disgust they expressed that we should even want to handle them. Their culture's traditions have left them with a deep-seated understanding that organisms and their ecosystems are dynamically connected to one another. With my study of the Cordilleran frogs, I hope to examine a small fragment of that dynamic connection.

Figure 4. Legends associating frogs with rainfall did not emerge only for obvious reasons. Tradition dating back to Incan culture, and possibly back to pre-Incan tradition, named not only the bright stars of the heavens, but also the negative space around the

stars—the “dark constellations”. Hanp’atu, “the Toad”, was a dark constellation that rose from the horizon synchronously with the first seasonal rains. Photo of one of our many camps, at Upispampa, by Emma Steigerwald.