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A MONITORING TECHNIQUE FOR HIGH-ALTITUDE HEADWATER STREAMS: A CASE STUDY IN THE HIGH ANDES

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Research on human impacts on *páramo*, grassland and wetland complexes characteristic of the Andean highlands, is a high priority, because economic development occurs quickly in this part of the world, multiple demands for water increase, and glacial water sources diminish in a warmer global climate (Buytaert *et al*. 2006). Headwater streams in *páramo* are especially sensitive to environmental perturbation, as they are oligotrophic and autotrophic, while developments like livestock pasturing, hydroelectric projects and mining are known to alter biota and chemistry of such streams (Milner and Petts 1994). Highly variable stream morphology, including expansive wetlands, small lakes disconnected from the drainage network, and frequent rerouting of surface or subsurface flows, typify the aquatic environment of *páramo* as a result of complex topography, soils and vegetation, characteristically rapid spatial and temporal changes in climatic factors, and a long history of human occupation in the high Andes (Buytaert *et al*. 2006). These factors present a challenge to stream sampling, as standard approaches and equipment (e.g., Fritz *et al*. 2006, Jones *et al*. 2006) require a minimum channel width and depth, continuous sections of overland flow, and habitat classification that may not be available in *páramo*.

The motivation for our study was to show that rapid water quality assessment can be adapted to the field conditions offered by *páramo*. To illustrate, we adopted the simple hypothesis that small-scale livestock pasturing deteriorates water quality and affects benthic community structure in two headwater streams located in the Chimborazo Faunal Production Reserve (Chimborazo), Ecuador. In the numerous villages within this high-elevation (3,700 to 6,310 m a.s.l.) reserve, residents supplement household income with pasturing. Water quality monitoring is essential to evaluating the sustainability of these livestock grazing practices within the reserve and to ensuring a supply of safe water for drinking and irrigation. We adapted the recommendations of the US Environmental Protection Agency (EPA) field manual for sampling headwater streams (Fritz *et al*. 2006). We also included methods recommended by the Ontario Benthos Biomonitoring Network (OBBN, Jones *et al*. 2006) to combine water quality testing and a survey of the benthic macroinvertebrate community. We expected both to be sensitive to the effects of low-intensity livestock grazing. We used this expectation to evaluate the effectiveness of our adapted methodology.

Our sample streams, Rio Blanco and Quebrada Toni, are located above 4,000 m a.s.l. on the westward, rainshadow region of the Chimborazo-Carihuaryazo massif (Sklenář and Lœgaard 2003). This region receives ca. 500 mm of rainfall per year (Clapperton 1990) with a high degree of monthly variability attributed to the dry and rainy seasons characteristic of the region. Mean annual temperature varies between 6 °C (4,000 m a.s.l., Skov and Borchsenius 1997) and 0 °C (5,000 m a.s.l., MEL 2012). The two streams were each divided into two sample reaches: one upstream of any pasture (“reference” reach) and one within the first downstream pasture (“treatment” reach). Reference reaches were in *páramo* subjected to low-intensity grazing only by llamas and vicuñas, while treatment reaches were surrounded by domestic cattle, sheep, and horses. We measured macroinvertebrate abundance, and calculated richness and diversity as Simpson’s index, and together with water quality parameters, carried out non-metric multidimensional scaling (NMDS). We applied a repeated-measures analysis of variance (ANOVA) to detect differences in stream water quality between upstream and downstream reaches.

Mauchly's sphericity tests confirmed multivariate normality for measures of conductivity (EC; $p = 0.90$), total suspended solids (TSS; $p = 0.91$), total dissolved nitrogen (TDN; $p = 0.66$), and pH ($p = 0.09$). Conductivity differed between ($F_{1,3} = 1180.9$, $p < 0.01$) and within ($F_{1,3} = 498.6$, $p < 0.01$) streams, although the within-stream difference was only observed for Rio Blanco ($F_{1,3} = 299.0$, $p < 0.01$). There were no detectable differences in TSS (between streams: $F_{1,4} = 4.5$, $p = 0.10$; within-stream: $F_{1,4} = 0.4$, $p = 0.56$), TDN ($F_{1,2} = 8.4$, $p = 0.10$; $F_{1,2} = 1.8$, $p = 0.31$), or pH ($F_{1,3} = 1.3$, $p = 0.34$; $F_{1,3} = 1.5$, $p = 0.31$).

Sixteen macroinvertebrates were represented among 1,610 sampled individuals (Table 1). Diversity and richness scores varied with reach, and were higher in downstream Rio Blanco only, as for EC. Corresponding to a trend of increased macroinvertebrate abundance and density in the downstream reaches of both streams, NMDS revealed higher TDN in downstream reaches and that differences in taxa assemblages between streams may be a result of more TSS in Rio Blanco (Figure 1). Baetidae corresponded best with high TDN and low TSS (i.e., pastured sites), whereas Hydrobiosidae, Glossophoniidae, and Hirudinae were most associated with low TDN (i.e., non-pastured sites). Pisidiidae, Scirtidae, Simuliidae, Ceratopogoninae, and Anthomyiidae all clustered around high TSS and medium TDN.

Our rapid stream assessment allowed us to consider several points regarding the effective sampling of high-Andean streams. Firstly, periodic deposits and mineralization of manure from livestock, combined with seasonal variability in the amounts of rainfall received on riparian areas, should lead to increased EC, and TDN and TSS movement into streams (Kauffman and Krueger 1984). However, measures of water chemistry alone only detected

Table 1. Hydrochemical stream characteristics and macroinvertebrate assemblages upstream and downstream of pasture.

	Rio Blanco Upstream	Downstream	Quebrada Toni Upstream	Downstream
Longitude	78°47'53.755"W	78°48'41.142"W	78°57'14.878"W	78°57'8.682"W
Latitude	1°23'57.881"S	1°23'13.724"S	1°27'1.189"S	1°27'21.299"S
Elevation (m a.s.l.)	4301	4135	4078	3990
Distance (km)	-	2.1	-	0.7
Width (cm)	20 – 35	10 – 70	10 – 15	15 – 25
Depth (cm)	10 – 20	10 – 50	5 – 15	10 – 20
Conductivity (uSi cm^{-1})	118 (98 – 132)	328 (304 – 375)	57 (49 – 66)	57(49 – 71)
pH	6.9 (6.8 – 7.4)	7.5 (6.9 – 7.8)	6.7 (6.2 – 7.3)	7.1 (6.7 – 7.6)
Total dissolved nitrogen (µg L^{-1})	182 (69 – 410)	239 (29 – 541)	220 (57 – 630)	318 (73 – 740)
Total suspended solids (mg L^{-1})	315 (96 – 524)	342 (252 – 404)	282 (44 – 468)	241 (84 – 484)
Taxon richness	8	14	10	10
Density (ind L^{-1})	19.8	28.2	9.8	17.8
Simpson's index	0.55	0.36	0.64	0.69
Taxon				
Non insect				
Hyalellidae	305	152	168	314
Planariidae	8	6	0	14
Naididae	7	10	6	8
Pisidiidae	0	36	1	2
Glossophoniidae	58	22	3	0
Hirudinae	29	42	1	0
Insect				
Baetidae	0	0	0	11
Hydrobiosidae	8	1	1	0
Rhyacophilidae	0	0	2	2
Scirtidae	0	6	0	0
Simuliidae	0	320	6	4
Tipulidae	0	1	0	3
Ceratopogoninae	0	1	0	0
Anthomyiidae	0	1	0	0
Tanypodinae	5	1	11	19
Chironomidae	2	2	12	1

Stream measurements are reported as means and/or ranges. Macroinvertebrate abundances are reported as frequency standardized by relative sample volume.

changes in EC, and not in TDN and TSS inputs. Surveying the macroinvertebrate community was essential to explaining variation within the headwaters of the Chimborazo reserve. Ordination of reach position and TDN by NMDS showed an association not detected by the repeated-measures ANOVA, and revealed certain taxa as potential indicators of site quality. Baetidae stood out as being most indicative of high TDN, and were only found in downstream Quebrada Toni, whereas an assemblage of Hydrobiosidae, Glossophoniidae, and Hirudinae was indicative of low TDN. The most conspicuous assemblage was Pisidiidae, Scirtidae, Simuliidae, Ceratopogoninae and Anthomyiidae, which corresponded to high TSS and medium TDN reaches. This assemblage was seemingly least sensitive to TSS, and has potential as an indicator high TSS in *páramo* streams.

Secondly, TSS best explained differences in community structure between streams. Elsewhere, an increase in EC and TSS has resulted in lower macroinvertebrate diversity and richness (Growns and Davis 1991, Mesa 2010). However, downstream Rio Blanco measured highest in TSS, richness, density, and diversity. It is possible that in oligotrophic systems a slight increase in EC and nutrient loading can also lead to a higher abundance of taxa tolerant of high TSS (Wohl and Carline 1996, Delong and Brusven 1998). Our study suggests that in the absence of increased TSS, subtle increases in EC and in nutrient loading in Rio Blanco may have resulted in greater macroinvertebrate abundance, richness and diversity.

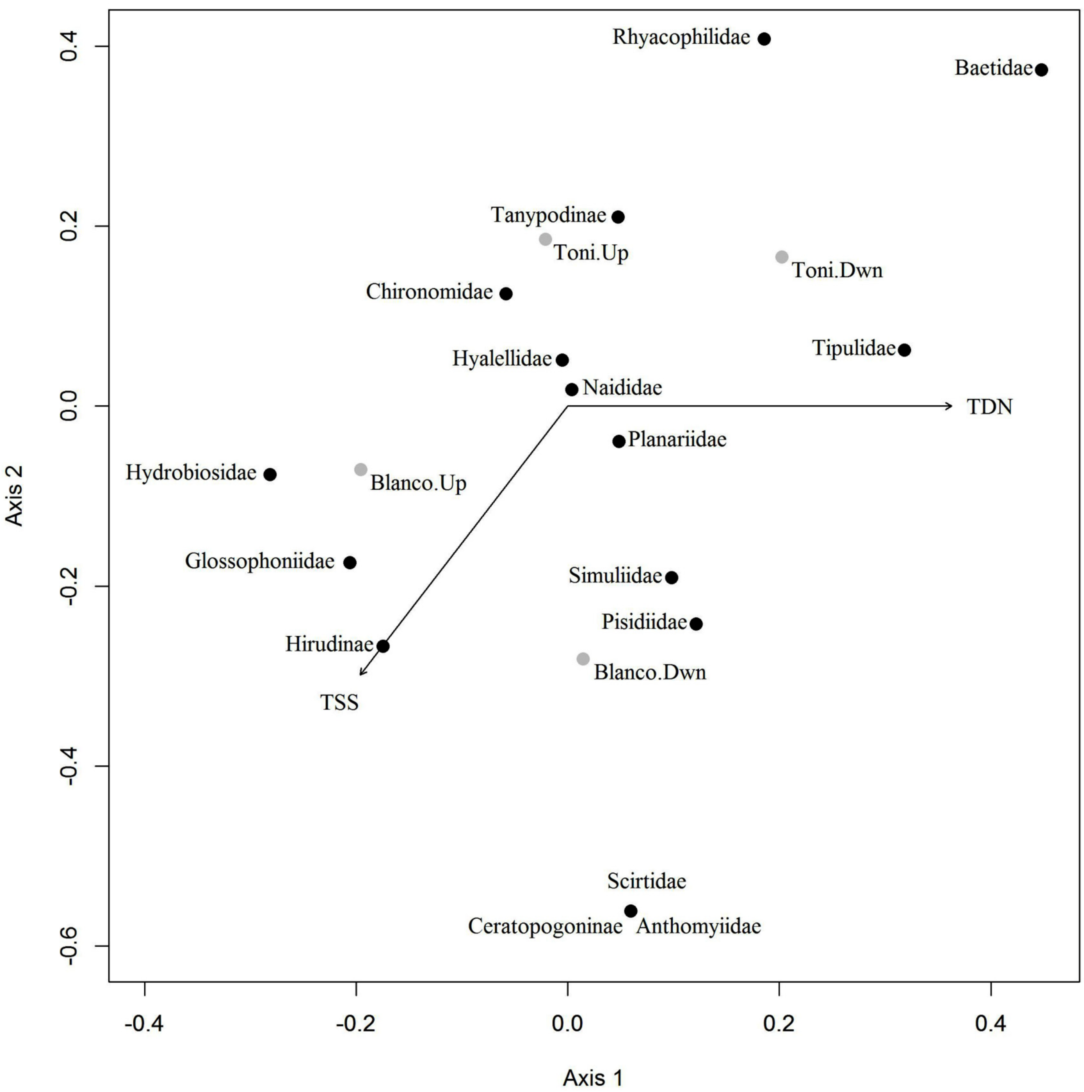

Figure 1. Projections of macroinvertebrate taxa, stream reach. Arrows represent correlations of environmental variables with taxa and reaches. Downstream positions are highly correlated with higher total dissolved nitrogen TDN.

This outcome is similar to what has been reported as an effect of nutrient loading in high-elevation streams elsewhere (Wellnitz and Rader 2003, Braccia and Voshell 2007, McIver and McInnis 2007). Jacobsen (1998) found that macroinvertebrate diversity in Andean streams responded positively to increased nutrient inputs and concluded that high-elevation streams are more sensitive to small amounts of nutrient loadings than lowland streams. The fact that *páramo* streams are largely oligotrophic also means that small increases in nutrients can raise primary productivity.

Lastly, the ordination result correlating higher TDN with downstream sample reaches was not consistent for TSS, suggesting the dominant pathway for nutrients into these streams is via subsurface rather than surface flows, where TSS may be filtered by wetland organic material. The extent of livestock pasturing in the Chimborazo reserve was likely below the threshold where erosion and soil compaction leads to excessive surface runoff of particulate solids. However, because our sampling took place during the dry season, we cannot rule out higher TSS inputs into streams during wetter parts of the year. Moreover, seasonal changes in macroinvertebrate abundance are characteristic of Andean streams, where abundance is typically lowest in the rainy season (Flecker and Feifarek 1994, Jacobsen and Encalada 1998, Mesa 2012). Jacobsen and Encalada (1998) proposed that TSS is an important contributor to seasonal variability in Andean streams. If so, soil compaction from livestock could exacerbate the increased TSS inputs expected during the rainy season, and possibly be more evident in upstream-downstream comparisons with more extensive water monitoring.

As explained above, *páramo* stream characteristics limit the ability to use standard sampling protocols. Simple adjustments to the EPA and OBBN guidelines were successful in sampling *páramo* streams in Chimborazo. The bucket method, standardized by volume rather than by number of sampling locations and time spent sampling, was sufficiently flexible to encompass the variable stream characteristics we encountered. By focusing on differences in macroinvertebrate community structure, our adapted sampling method indicated that livestock pasturing has a stream effect in the *páramo* of the Chimborazo reserve. A shortcoming of our method was pooling field-sorted macroinvertebrates, eliminating the ability to construct species-volume curves to validate sample size sufficiency. Future use of our method should isolate specimens between each bucket sampling to allow for such analyses.

As there is no standard stream sampling protocol or regional monitoring program for high-Andean streams, establishing a systematic approach to stream monitoring is crucial to sustainable management of the Chimborazo Faunal Production Reserve. This study represents the first published attempt to reconcile this weakness in light of impending hydroelectric projects and other economic development in the region.

MATERIAL AND METHODS

We sampled during the end of the 2009 dry season, during August and September. To reduce the effect of within-stream spatial heterogeneity, downstream sample reaches (treatment sites) were located relatively close in elevation (< 200 m) and distance (< 2 km) to upstream reaches (reference sites). Stream sizes ranged from 10 to 70 cm in width and 5 to 50 cm in depth, with a high degree of variability within each reach. As other approaches to sampling would not be sufficiently flexible given this variability, we used bucket sampling (Fritz *et al.* 2006). The EPA guidelines recommend delineating a 30 m stream reach in which eight samples are to be collected, four from erosional and four from depositional habitat types. However, the availabilities of continuous 30 m sections containing both habitat types were scarce due to subsurface flow. In the upper Quebrada Toni, the only sites of sufficient width, depth, and volume of water were of erosional habitat. Therefore, we chose to focus our analysis on erosional sites, because they were present in all the reaches we studied. Stream substrate was disturbed by scraping and lifting rocks with a trowel in a 1 m stretch of stream, upstream of a 5 L plastic pan, which was repeatedly filled until ca. 100 specimens were collected, and until 5 to 15 L of streamwater was collected from at least three locations along each reach. Taxa abundances are reported as frequencies corrected to 10 L. Benthic material was immediately filtered through 25, 2, and 0.5 mm sieves, and macroinvertebrates were field sorted into taxonomic orders and preserved in > 70% ethanol. Specimens were later identified to family. Water samples were taken from each reach on three different dates between August 31 and September 16, 2009 (Table 1) and analyzed using standard methods.

A repeated-measures analysis of variance (ANOVA) was used to detect differences in water chemistry. Assumptions of multivariate normality were tested with Mauchly's sphericity test. Listwise deletion was used for missing measurements of TDN, EC, and pH. The ANOVA model applied marginal sums of squares to account for imbalance resulting from missing data. Macroinvertebrate community structure was described in terms of density, taxa richness, and Simpson's index. Taxa richness was calculated as the total number of taxa occurring at each sample reach (Jongman *et al.* 1995). Non-metric multidimensional scaling (NMDS) was used to explore relationships among macroinvertebrate taxa, TSS, TDN, and upstream-downstream reaches. Conductivity and pH were omitted from the final ordination as EC did not accurately correlate with raw abundance data, and the upstream-downstream relationship of pH and macroinvertebrate abundance was meaningless. To more clearly illustrate environmental relationships with raw abundance data, the ordination was rotated so that TDN was parallel with axis 1. All statistical analyses were performed using R statistical software (R Core Team 2013). The repeated-measures ANOVA and NMDS were carried out using the Anova function in the car package (Fox and Weisberg 2011) and the metaMDS function in the vegan package (Oksanen *et al*. 2013) respectively.

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