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Ecological Constraints on Violence Avoidance Tactics in the Prehispanic Central Andes

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ABSTRACT
Prehispanic agricultural populations in the central Andes exhibit some of the highest rates of lethal and sublethal trauma ever recorded. Explanations for high rates of violence focus on what factors drove proactive conflict. While it is true that incentives for proactive violence must exist for high rates of trauma to ensue, it is far less recognized how ecological conditions may promote economic activities that constrain violence avoidance tactics and thus influence rates of violence. Here, we draw on models from behavioral ecology to generate predictions about how violence co-varies with environmental gradients, related subsistence strategies, and attendant defensive tactics. We hypothesize that rates of violence will be highest in marginal and variable environments where high-mobility subsistence strategies serve to reduce subsistence risk while increasing the costs of violence avoidance. Our results show that high elevation locations with variable topography where high mobility subsistence strategies are common exhibit the highest rates of generalized interpersonal violence. These results suggest that as ecological conditions become marginal and variable, risk-reducing subsistence strategies are emphasized, which result in increased exposure to violence. This study shows that environmental influences on the efficacy of violence avoidance tactics are important for explaining variability in rates of violence.

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Trauma; warfare; human behavioral ecology; risk reduction; environmental archaeology; conflict

Introduction

Prehispanic agricultural populations in the central Andes exhibit some of the highest rates of lethal and sublethal trauma ever recorded (e.g. Arkush and Tung 2013; McCool et al. 2020; Scaffidi and Tung 2020; Tung 2008). Explanations for high rates of Andean violence vary (Arkush 2008; McCool et al. 2022a; Tung 2008) but focus on the factors driving proactive intergroup violence. Implicit in these explanations is that the observed rates of violence must be the result of high payoffs for participation in warfare. While it is certainly true that incentives for proactive violence must exist for high rates of trauma to occur, it is equally true that when violence is high, individuals should engage in violence avoidance tactics that lower the likelihood of unwanted violent encounters. Therefore, when high trauma rates persist, it may be the result of ecological conditions promoting economic strategies that limit violence avoidance tactics, the result being higher rates of intergroup violence. Afterall, the proportion of a population killed or injured by intergroup violence is the result of both proactive violence and the efficacy of violence avoidance strategies (Milner, Anderson, and Smith 1991).

Here, we draw on risk-sensitive models from human behavioral ecology (HBE) to produce and test qualitative predictions regarding how rates of violence co-vary with environmental gradients, related subsistence strategies, and attendant defensive tactics to evaluate how ecological conditions may restrict people's ability to avoid violent encounters. Risk-sensitive models suggest that all else being equal, in two environments that offer equal incentives for intergroup violence but impose divergent costs for violence avoidance, rates of intergroup violent encounters (and resulting trauma rates) should be higher in the environment where defense is more costly (Figure 1). Following this logic, we propose that high rates of violence in the central Andes are in-part due to subsistence-security tradeoffs resulting from economic strategies that favor high subsistence mobility and temporary settlement (or household) dispersion in highland regions that limit defensive investment. These factors are the result of agropastoral and field-scattering subsistence strategies used in highland environments to cope with marginal and stochastic agroecological conditions. These highland strategies, while effective at reducing economic risk (Browman 1987; Goland 1993), increase the costs of violence

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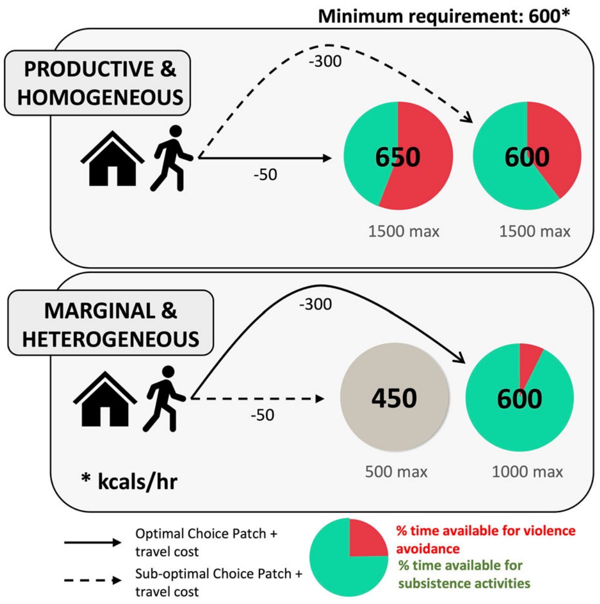

Figure 1. A visual schematic of the subsistence-security tradeoff model. In this simplified world an individual needs 600 kcal/hr for survival (an arbitrary threshold). The top panel depicts a productive and homogeneous environment with two resource patches: one near to home (left) and one further away (right), each with a maximum return (no travel cost and all time spent on subsistence) of 1500 kcal/hr. The bottom panel depicts a marginal and heterogeneous environment with maximum returns (no travel cost and all time spent on subsistence) of 500 and 1000 kcal/hr respectively. Prior work suggests the probability of a violent encounter increases with distance from a central place. Similarly, greater travel distance may decrease the amount of time an individual can invest in violence avoidance. Thus, in a homogeneous and productive environment an individual could spend significantly more time in violence avoidance activities while still obtaining greater returns by conducting subsistence activities in the close patch. Even in a distant patch, they may be able to invest heavily in violence avoidance or decide to leave the patch sooner. In a marginal and heterogeneous environment, nearby patches may not be viable (here < 600 kcal/hr returns), meaning the distant patch is higher ranking and thus exploited. However, the greater distance travelled in a poor environment may leave little to no time for violence avoidance, exposing the individual to an even higher probability of a violent encounter.

avoidance and may result in greater intergroup violence exposure. Tradeoffs between subsistence and security suggest that ecologically imposed costs on violence avoidance tactics may be just as important as motivations for proactive violence for explaining variability in rates of intergroup violence.

The Subsistence – Security Trade-off

The last twenty-five years of anthropological research has seen a dramatic increase in studies on intergroup human violence (Allen et al. 2016; Arkush and Allen 2006; Daly 2017; Gat 2015; Glowacki and Wrangham 2013; Glowacki, Wilson, and Wrangham 2017; Gómez et al. 2016; Keeley 1996; Kelly 2000; LeBlanc 1999; Macfarlan et al. 2014; McCool et al. 2022b; Milner 1999; VanDerwarker and Wilson 2016; Walker 2001). This research has produced ample evidence showing lethal and sublethal violence to be a pervasive, albeit variable, human behavior. High levels of violence raise the inevitable question: what behaviors evolved to reduce the risk of interpersonal violence, and at what cost?

Archaeological and ethnographic data suggest that the costs of intergroup violence avoidance largely manifest as subsistence constraints and related dietary stress (Glowacki and Wrangham 2013; Hickerson 1970; Human Security Report 2005; Keeley 1996; Kelly 2005; McCool 2020; Meggitt 1977; Netting 1973; Roscoe 1996; VanDerwarker and Wilson 2016). Numerous studies of small-scale warfare show that when the risk of interpersonal violence is high, subsistence travel is dangerous and should be avoided (Glowacki and Wrangham 2013; Hickerson 1970; Keeley 1996; Kelly 2005; Milner 1999; Meggitt 1977; Netting 1973; Roscoe 1996; VanDerwarker and Wilson 2016). Unfortunately, basic biological demands necessitate a compromise between violence avoidance and resource acquisition. Where subsistence demands necessitate high-mobility and/or population dispersal, violence avoidance tactics will be costly to employ and maintain (McCool 2020).

Previous research has shown that as the frequency and severity of intergroup violence increases, the probability of an interpersonal violent encounter may increase disproportionately based on an individual's distance from a central place, with more distant resource patches exhibiting a higher probability of a violent confrontation, and therefore a greater need for investing in violence avoidance tactics. This is due to three factors: (1) humans generally practice a subsistence system whereby aggregations of people temporarily disperse into smaller parties that are more vulnerable to attack or ambush (Gat 2015; Glowacki and Wrangham 2013; Keeley 1996; Kelly 2000, 2005; Milner, Anderson, and Smith 1991; Roscoe 1996, 2008), (2) a related point, there is safety in numbers at a home base, and (3) resource patches further from a central place favor longer in-patch residence times (Bettinger and Grote 2016; Charnov 1976), increasing the time spent away from protected central places. Extensive ethnographic and archaeological data on small-scale societies shows that the majority of victims of intergroup violence are isolated groups or individuals moving outside of protected central places (e.g. Bayham, Cole, and Bayham 2019; Gat 2015; Glowacki and Wrangham 2013; Heider 1979; Hendrickson, Mearns, and Armon 1996; Keeley 1996; Kelly 2000, 2005; Milner, Anderson, and Smith 1991; Netting 1973; Roscoe 1996, 2008). These studies demonstrate a subsistence-security tradeoff, whereby living in population clusters affords greater safety relative to dispersed populations, and exposure to violence increases with time and distance away from protected central places (see, Figure 1). It is not surprising then that chronic warfare often promotes population aggregation (LeBlanc 1999), reduced mobility (Kelly 2000), buffer zones (Bayham, Cole, and Bayham 2019; DeBoer 1981), and the implementation of natural and artificial fortifications to protect central places (Arkush and Stanish 2005; Field 2008; McCool 2017). Nonetheless, socioecological conditions can increase or decrease the costs of violence avoidance tactics. For example, nomadic pastoralists living in arid deserts will suffer high costs for congregating into large, formidable groups relative to sedentary agriculturalists living in productive habitats. As such, optimizing the tradeoff between security and subsistence will be critical and based in part on the abundance and distribution of local resources. To evaluate the effects of the subsistence-security tradeoff we examine how changes in central Andean environmental gradients structure subsistence mobility and population dispersion – both of which influence the costs of violence avoidance. In particular, we focus our study on high elevation Andean environments, where local conditions foster greater subsistence mobility and seasonal group dispersion relative to low elevation locations.

The Andean Highlands and Economic Diversification

The Andes has a strong tradition of environmental research, particularly as it pertains to ecological variability and its effect on economic strategies (e.g. Goland 1993; Kolata 1986; Murra 1972; Troll 1968; Vidal 1981; Winterhalder and Thomas 1978). The central Andes in particular is characterized by spatially diverse geoecological and climatological conditions that are strongly linked to elevational and latitudinal gradients (Troll 1968; Winterhalder and Thomas 1978). Critical agricultural factors such as altitude, slope, aspect, soil type, moisture, and the amount of solar radiation vary considerably within small areas and over short time periods (Contreras 2010; Winterhalder and Thomas 1978). In the central Andean highlands, rainfall is constrained to a short austral summer season (ONERN 1971; Winterhalder and Thomas 1978) offering limited and highly variable moisture regimes that make environmental conditions unpredictable. These factors produce patchily distributed and irregularly timed agroecological conditions that are most often defined as marginal (Contreras 2010; Zimmerer 1999). In addition, the young and poorly developed highland soils have low moisture retention and lack certain crop buffering nutrients (Winterhalder and Thomas 1978). These conditions, while wide-spread in the central Andes, vary considerably by elevation and latitude (Gerdau-Radonić et al. 2015; Winterhalder and Thomas 1978). Increasing altitude produces colder temperatures, increased precipitation, strong evaporative winds, and frequent nightly frosts. Moving south through latitudinal gradients sees increases in aridity due to declining precipitation.

These challenging conditions make highland food returns highly variable and unpredictable, leading to difficulties maintaining adequate food supply. As a result, many highland populations frequently face resource scarcity and attendant health problems (Winterhalder and Thomas 1978). It is not surprising then that highland subsistence strategies are closely attuned to local environmental conditions such that subsistence strategies vary in coordination with agroecological diversity. Indeed, Wilson et al. (2022) find that climatological and environmental variables explain a significant proportion of dietary variability in the Prehispanic Andes as measured by stable nitrogen and carbon isotope values. Wilson et al. empirically demonstrate that local environmental conditions strongly correlate with subsistence strategies and resultant dietary signatures.

Subsistence patterns in the highland environments most often rely on a suite of economic diversification strategies to mitigate subsistence risk (Figure 2) (Browman 1987; Goland 1993; Kuznar 2001; Valdivia, Dunn, and Jetté 1996). Agropastoralism and agricultural field scattering provide key risk-reducing benefits that trade-off with increased travel and transportation costs (Browman 1987; Goland 1993; Marston 2011). The high subsistence mobility (i.e. frequent travel to produce/obtain food that is often far away) that results from agropastoralism and field scattering is key to our hypothesis concerning the relationship between ecological conditions and the efficacy of violence avoidance tactics. As such, an extended treatment of these two strategies is warranted.

Agropastoralism in the Andes

Domestic camelids (llama and alpaca) provide a number of useful primary products including meat and blood and secondary products such as wool and dung for fuel or fertilizer (Browman 1997). Pastoralism takes two economic forms – specialized pastoralism and agropastoralism (Nielsen 2009; Parsons, Hastings, and Matos 1997). Specialized pastoralism entails the full-time management of camelid herds and the paucity of crop production. While populations living above 4,000 MASL sometimes engage in this type of economy (e.g. Flores Ochoa 1977), specialized pastoralist diets are heavily supplemented by domesticated crops that are obtained through frequent exchange with communities living at lower elevations (Browman 1974; Parsons, Hastings, and Matos 1997). Agropastoralism, the more common highland

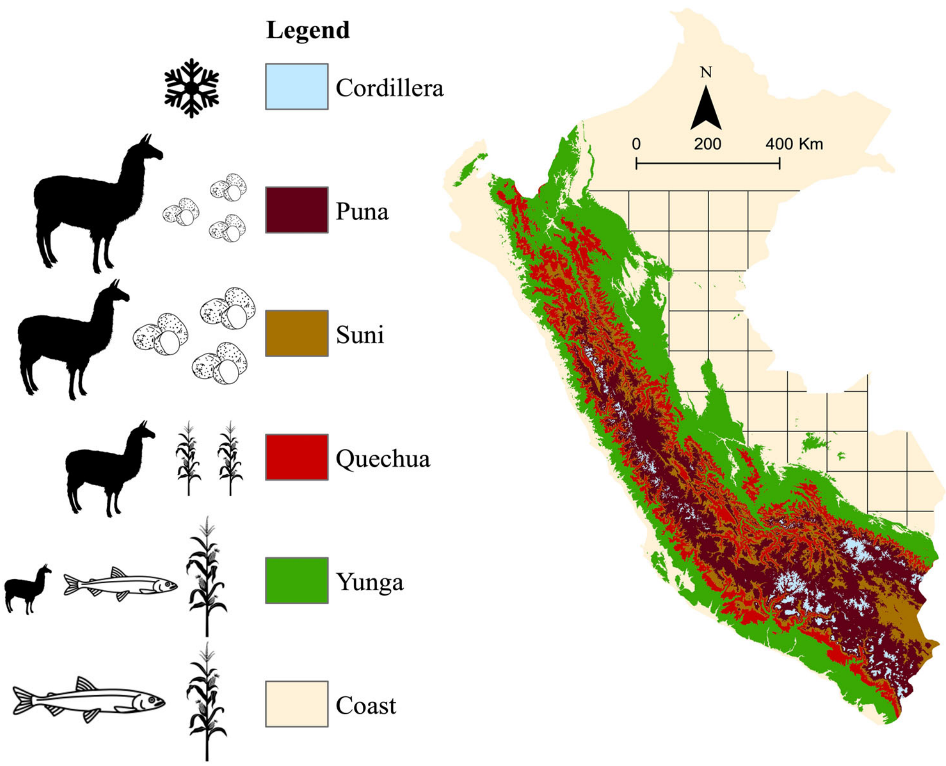

Figure 2. Generalized scheme of subsistence change with elevation (meters above sea level, MASL) and ecotone focusing on the Peruvian Andes. The size of the icons illustrates economic reliance. The number of agricultural icons delineates the reliance on field scattering. The Coast layer (0–500), Yunga (501–2300), Quechua (2301–3500), Suni (3501–4000), Puna (4001–4800), and Cordillera (>4800) ecotones follow standard conventions (e.g. Dufour et al. 2014). Cross-hatched area is the selva (jungle) ecology and is not included in this study due to the lack of trauma samples.

economic strategy (Browman 1974, 1987, 1990; Capriles 2014; Flores-Ochoa 1968, 1977, 1979; Flores Ochoa and Kobayashi 2000; Orlove 1977), combines cultivation and herding into a more diversified economy. Typically, populations living on the altiplano (>3,500 MASL) combine herding with the cultivation of frost-resistant tubers and grains (Nielsen 2009). Mid-altitude agropastoralists rely more heavily on meso-thermic cultivars such as maize and quinoa. As one travels down slope towards the coast, agriculture is emphasized over pastoralism (Murra 1972; Nielsen 2009; Parsons, Hastings, and Matos 1997) and the dietary input of marine resources becomes more important (Figure 2) (Gerdau-Radonić et al. 2015; King et al. 2018; Marsteller, Zolotova, and Knudson 2017; Prieto and Sandweiss 2019). Indeed, subsistence herding is rare below 3,000 MASL due to declining forage abundance (Aldenderfer 2006) and the increasing productivity of agricultural and marine economies (Nielsen 2009).

This is not to say that coastal pastoralism was non-existent in pre-contact times, as there is some evidence for small-scale herding, largely for ceremonial purposes (Dufour et al. 2014; Szpak et al. 2014). However, most of the coastal zooarchaeological evidence indicates a highland origin for camelids that were later brought to the coast for consumption (Szpak and Valenzuela 2020), and the majority of evidence points to an emphasis on herding economies as altitude increases.

Agropastoralism is hypothesized to be a risk-reducing strategy for coping with the marginal and unpredictable highland ecology (Browman 1987; Capriles 2014; Kuznar 2001; Tripcevich and Capriles 2016; Valdivia, Dunn, and Jetté 1996). It is argued, and there is a fair amount of evidence in support, that agropastoralism acts as an economic diversification strategy that reduces yield variance and spreads the probability of economic failure among multiple subsistence strategies (Browman 1974, 1987; Capriles 2014; Kuznar 2001; Valdivia, Dunn, and Jetté 1996). Diversification helps ensure harmful perturbations impact alternative economic strategies independently, decreasing the probability of shortfalls (Goland 1993; Kuznar 2001). Pastoralism is especially beneficial in highland ecologies where agricultural productivity is marginal and variable due to patchy distributions of arable land, frequent nightly frosts, poor quality soils, steep slopes, severe erosion, unpredictable precipitation, and strong evaporative winds (Contreras 2010; Goland 1993; Kuznar 2001; Nielsen 2009; Winterhalder and Thomas 1978).

Some have hypothesized that Prehispanic lowland and coastal populations maintained herds using maize as fodder, thus removing the need for natural forage habitat (Dufour et al. 2014). However, this practice should be rare as it defeats the primary economic benefit of pastoralism – risk reduction. During periods of low agricultural yields human populations will suffer by allocating scarce crop resources to dependent herds, and pastoralism will be unable to reduce economic yield variance (i.e. risk) because herds cannot be sustained independent of farming such that crop failure will produce herd failure. As such, maize-dependent herds may exist as a small-scale practice but should not be expected to be an important subsistence strategy.

Despite the advantages of agropastoralism, herding is not without its challenges. Overgrazing is a major concern for herders, as it degrades soils, increases erosion, and can promote the growth of toxic plants and other factors that reduce the quality of grazing habitat (Browman 1974, 1987, 1997; Capriles 2014; Parsons, Hastings, and Matos 1997). Overgrazing is prevented by regular movement of herds between patches to reduce the spatial-extent and intensity of forage depression (Browman 1987; Kuznar 1991). Occasional burning of grazing habitat may also improve yields by removing undesirable flora such as woody shrubs and fostering the growth of favorable forage (Browman 1974). Burning cannot however prevent overgrazing and is typically beneficial only if conducted every 3–5 years (Browman 1974).

During periods of drought, vegetative growth is suppressed and grazing patches become less productive. For example, during the 1982–1983 highland drought, pasture was reduced by 50% in some regions (Browman 1987). Drought is particularly harmful in arid regions that receive <500 mm of annual precipitation, where limited baseline forage combines with seasonally inadequate or ill-timed precipitation to lower habitat carrying capacity and prevent fat accumulation in immature camelids (Browman 1987). Drought can also decrease female camelids' ability to produce sufficient milk to sustain immature camelids, leading to starvation (Kuznar 1991).

Both overgrazing and drought reduce the carrying capacity of grazing habitat and limit individual fat content both of which reduce net caloric returns (Browman 1987). A strategy for coping with seasonal scarcity or declining forage is herd movement to prevent overgrazing and to target ephemeral or dispersed grazing habitat (Browman 1974, 1987; Kuznar 1991). While herds may be sustained temporarily on grazing patches adjacent to settlements or on fallow/post-harvest agricultural fields, this practice leads to intensive overgrazing (Browman 1987) and cannot be maintained indefinitely. This strategy is particularly ineffective where available land is limited, populations are dense, and low baseline (or seasonal) precipitation inhibits the growth of adequate forage. Nonetheless, the degree of residential mobility and seasonal travel for agropastoralists is dependent on the availability of local forage and trade-offs with agricultural requirements.

To summarize the key points, herding strategies require high mobility and frequent movement between pasturage to cope with local forage shortages and prevent overgrazing (Browman 1987; Kuznar 2001). Frequent movement comes into conflict with agricultural strategies, which favor sedentism and require intensive labor inputs, particularly at the end of the dry season – precisely the same time herds need to be taken up to pasturage. This creates a time-allocation trade-off, whereby energy invested into one strategy decreases potential yields from the other (Parsons, Hastings, and Matos 1997). Further, agropastoral populations tend to locate themselves adjacent to farming patches, even if these areas are distant from herding pastures (McCool 2020). This is due to the fact that highland agricultural fields require consistent and frequent maintenance (Goland 1993; Parsons, Hastings, and Matos 1997) and because domestic crops often provide the bulk of dietary caloric inputs. The result is a settlement pattern that limits travel to agricultural fields but requires extended trips and frequent mobility to and from pasturage (Parsons, Hastings, and Matos 1997). While the time-allocation trade-off can be optimized to maximize agricultural and pastoral returns within these constraints, it also has the potential to increases the costs of violence avoidance tactics by requiring population or household dispersal, frequent mobility, and long-distance travel.

Exacerbating these costs further, domestic camelids represent a dense, high-return, and mobile package which is especially attractive to thieves and raiders (Glowacki and Wrangham 2013, 2015; Flannery, Marcus, and Reynolds 1989; Kuznar 1991). Even in modern times, highland pastoralists can expect to lose 10–20% of their herd from theft (Kuznar 1991). Thus, all else equal, high mobility strategies that promote population dispersion (i.e. specialized pastoralism or agropastoralism) should entail a higher exposure to violent interactions relative to the lower mobility strategies (i.e. full-time agriculture and mixed intensive fishing-farming).

Field Scattering

Field scattering has received considerably less attention in the economic and subsistence literature than agropastoralism. Nonetheless, there is strong evidence suggesting field scattering is an effective and common risk-reducing strategy favored in highland environments similar to those that promote herding (Goland 1993; Valdivia, Dunn, and Jetté 1996). This is because field scattering is a means of spreading the probability of crop loss across multiple plots placed in varying microenvironments (Goland 1993; Marston 2011;

Winterhalder 1990). Field scattering has been recorded most often in high elevation locations where agricultural conditions are marginal, variable, and face many crop loss hazards (e.g. nightly frosts) (Goland 1993). The costs of field scattering are a reduction in maximum yields due to increased travel and transportation time to and from dispersed farm plots. As with agropastoralism, field scattering entails a higher threat of violent encounters relative to the lower mobility strategies (i.e. field clustering). We assume that field scattering will co-occur with agropastoralism, such that the practice will be at higher frequency as elevation increases and becomes more variable, and latitude declines.

Despite the ample information on herding and agricultural ecology, it is a challenge to reconstruct the abundance, distribution, and dependence on pastoral and agricultural resources throughout Andean prehistory (Capriles 2014). Nonetheless, it is possible to evaluate herding and field scattering by proxy using the spatial distribution of environmental conditions couched in existing knowledge of ecology and economy. Given that the reliance on herding and field scattering generally increases with elevation and distance from the coast (which are often correlated), and that herding and field scattering are most commonly practiced as risk-reducing strategies in highly variable environments, we can measure the effect of herding and field scattering on violence using geographical gradients. We accomplish this using elevation and latitude, both of which have been shown to heavily structure variation in ecological and climatological conditions (Contreras 2010; Kolata 1986; Murra 1972; Pulgar Vidal 1981; Sandweiss and Richardson 2008; Tosi 1960; Troll 1968; Winterhalder and Thomas 1978). We use mean and standard deviation in elevation as proxies for ecological marginality and heterogeneity, with risk-reducing strategies most common in high-elevation locations with patchily distributed resources, as discussed earlier. We use latitude as a proxy for overall ecological productivity, as precipitation and temperature tend to increase in higher central Andean latitudes (e.g. Ecuador) relative to lower latitudes (e.g. Bolivia) (Wilson et al. 2022).

Local Ecology and Sociopolitical Complexity

Complex, multiregional polities often exert strong effects on the diets and subsistence strategies of subordinate and neighboring populations (Kellner and Schoeninger 2008; Toyne et al. 2017; Williams and Melissa 2013). Indeed, there is some evidence that imperial periods lead to an increase in non-local dietary inputs and render local ecological conditions less important for determining dietary composition and nutrient levels. Cross-regional studies in the Andes suggest that diets become less structured by local conditions during the Middle Horizon (500–1000 CE) and Late Horizon (1450–1532) imperial periods (Kellner and Schoeninger 2008; Toyne et al. 2017; Wilson and McCool forthcoming; Williams and Melissa 2013). As such, imperial periods may weaken the correlation between local ecological conditions, economic diversification and attendant mobility. If so, we expect the relationship between ecological variation and violence to weaken or be less consistent during imperial periods relative to periods of greater local autonomy.

Hypothesis and Predictions

In pastoral and agricultural systems, the payoffs for violence are highest when individuals compete for high-ranking resources that are scarce and distributed in patches that can be effectively privatized (Allen et al. 2016; Georgiev et al. 2013; McCool et al. 2022b). This expectation ties into research on territoriality, which predicts resource defense will yield high payoffs when resources are clustered and predictable, with the benefits of exclusionary tactics increasing when resource patches are scarce, the costs of losing resources to theft are high, and additional increases in population density will lower average returns (Allen et al. 2016; Dyson-Hudson and Smith 1978; Fretwell and Lucas 1969). However, if we assume that those incentives are roughly equal everywhere, the rates of actual violent encounters, and thus rates of violent trauma, will peak where the costs of violence-avoidance are highest, as is the case for individuals who rely increasingly on pastoralism and field-scattering strategies. From this hypothesis, we derive three alternative but related predictions and two interaction predictions, followed by expectations of how these relationships might change during periods of varying sociopolitical complexity.

Elevation. Economic reliance on herding and field scattering increases with elevation. As such, we predict that (P1) as elevation increases, rates of violent trauma should increase. We also expect that greater variability in elevation proxies increased ecological variability, which should promote greater emphasis on high-mobility risk-reducing strategies. As such, we predict that (P2) rates of violence will positively co-vary with standard deviation (SD) in elevation.

Latitude. The Andean cordillera exhibits latitudinal changes in temperature, precipitation, and the amount of altiplano habitat that is ideal for herding (Winterhalder and Thomas 1978). This latitudinal gradient renders agriculture less productive and reliable and pastoralism more profitable moving from north to south. This should entail increased subsistence mobility and violence exposure. As such, we predict that (P3) rates of violence should be higher in southern latitudes relative to northern latitudes.

Interactions. We might expect significant interactions between predictor variables, such that violence peaks where environmental variables interact. Specifically, we predict that (P4) rates of violence should be highest in high elevation locations in southern latitudes, where agropastoralism and field scattering will be most advantageous. We also predict (P5) rates of violence to be highest in locations where mean elevation and SD in elevation interact (i.e. places where elevation is high and topographically variable).

Complexity. If political complexity alters or interrupts the link between local ecological conditions and rates of violence, we expect the Middle Horizon (500–1000 CE) samples in our dataset to exhibit a weak or non-significant relationship with elevation and latitude relative to samples from the Late Intermediate period (1000–1450) when local autonomy most defined regional sociopolitics (Covey 2008; Parsons and Hastings 1988).

Methods

Violent trauma database. The trauma database derives from several dozen peer-reviewed publications that report proportions of violent ante-mortem and peri-mortem skeletal trauma from the central Andean region. This database contains counts of violent skeletal trauma (excluding accidents and post-mortem damage) as a proportion of total skeletal sample for each site or region. Our skeletal trauma database only contains data from adults to avoid taphonomic and cultural biases that skew the number of subadults and result in uneven adult to subadult ratios between samples. We also only include craniofacial trauma, which is a standard practice in Andean bioarchaeology (Arkush and Tung 2013), to avoid bias due to differential representation of postcranial remains in skeletal samples. Published data that reports ante-mortem and peri-mortem craniofacial trauma were included if they (1) report the overall proportion of trauma, (2) contain a sample size of 30 individuals or greater to reduce potential bias in reported trauma percentages due to small sample sizes, and (3) contain site or region-specific locational data (i.e. the location of the archaeological cemetery context is reported). In all, 28 Andean samples comprising a total of 3,471 individuals make up the database (Figure 3), which is available in Supplement A.

Elevation and Latitude. Elevation is determined using a 30 m digital elevation model (DEM) (Figure 3). For each skeletal trauma sample a spatial centroid was recorded with a 10 km buffer generated around the centroid. Mean and standard deviation (SD) elevation are extracted for the area within the buffers around each site. Latitude is extracted from the spatial coordinates in the database. A 10 km buffer was selected to capture an average daily travel bout, assuming a 20 km (12mile) roundtrip will approximate a maximum daily distance. While a 10 km buffer is somewhat small, our aim is to capture the local environment immediately surrounding the residential sites. In the central Andes where elevation and environment change substantially over short distances, it is important to avoid the pitfalls of casting a net too widely that may pick up geographic features (e.g. mountain peaks) that are not related to local subsistence.

Complexity. We include time period in several models to test our expectations for both the imperial Middle Horizon period and regionally autonomous Late Intermediate period. Additional periods were not included in the analysis due to the paucity of available trauma samples.

Statistics. To test our hypotheses, we fit generalized linear models (GLMs) with a binomial distribution and log link appropriate to proportional data, with a quasibinomial estimation to account for dispersion in our response variable. We first generated three bivariate GLMs comparing our response variable (generalized trauma) to each of our predictor variables (mean elevation, SD elevation, Latitude). We then specified models for each of the predictor variables for LIP trauma data only and models with all trauma data and time period as an interaction term to assess how complexity influences observed trends (Table 1). For significant models (either bivariate or with time period as an interaction term) we then specified a multivariate model that includes all significant predictor variables and a model to evaluate interactions between our significant predictor variables. We then ran Likelihood Ratio Test (LRT) ANOVAs for multi-model comparison. To test for spatial autocorrelation, we generated 999 Monte Carlo Simulations of a Moran's I test. Results are non-significant ($I = -0.003$, $p = 0.3740$), indicating no spatial autocorrelation in our response variable. All analyses are conducted in the R programming environment (R Core Team, 2020) and are available in Supplement B.

Results

As shown in Tables 1, when time period is not accounted for mean elevation (model 1) weakly positively co-varies with generalized trauma and standard deviation (SD) in elevation (model 3) significantly positively co-varies with generalized trauma with a moderately strong effect, with latitude having no significant effect (model 5). When time period is included as an interaction term, mean elevation significantly co-varies with generalized trauma for both the MH and LIP (model 6), albeit in opposite directions – violence decreases with mean elevation during the MH and increases with mean elevation during the LIP (Figure 4). Both MH and LIP trends positively co-

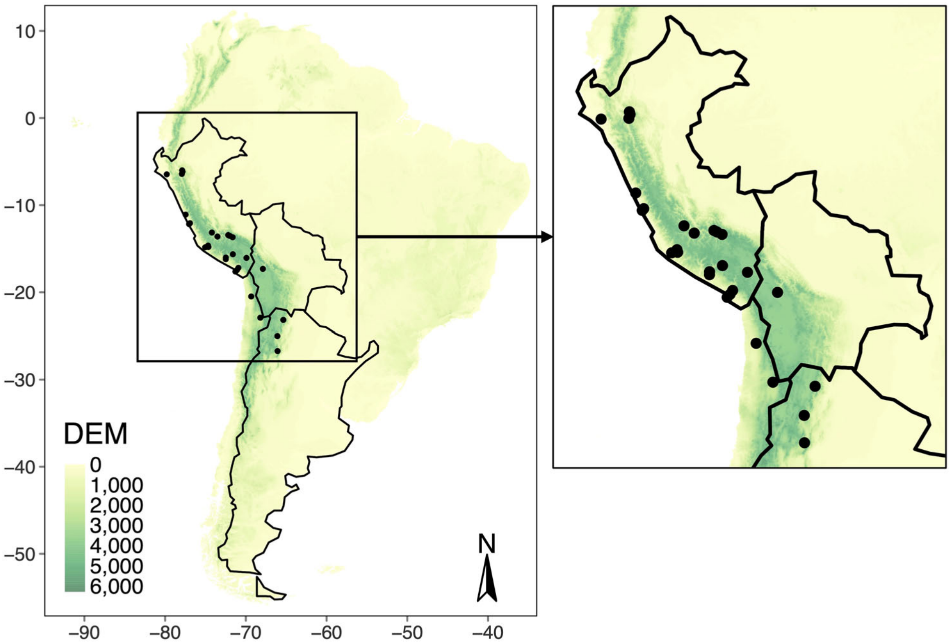

Figure 3. A Digital Elevation Model (DEM) for the central Andes. Black points represent the trauma samples in our database.

vary with standard deviation in elevation (model7, Figure 4), although only the LIP is significant. The latitude model (model8) has non-significant terms even when time period is accounted for.

Multivariate models that only include LIP violent trauma show that a more complicated model that includes both mean and SD of elevation (model 9) is a significantly better fit than the bivariate models (Table 2, LRT $p = 0.013$), while a model with mean elevation as the predictor and SD elevation as an interaction term (model 10) is the best fit of the bivariate and multivariate models (Table 2, LRT $p = 0.0197$). These results provide some support for P1 and P2, but only for the LIP. The relationship between elevation and violence is largely opposite during the Middle Horizon, supporting the expectation that the predicted relationships break down during imperial phases. The models comparing trauma to latitude are non-significant, providing no support for P3 or P4. The model comparing LIP trauma to mean and SD elevation as interaction terms is significant and the best fit of LIP-only models, providing strong support for P5 (Figure 5). To summarize, the strongest correlates of generalized rates of violence are mean elevation and SD elevation with the direction of relationship supporting our predictions for the LIP, when regional autonomy defined the central Andes, and opposite or weak during the MH, when the Wari and Tiwanaku states controlled much of the central Andes. The models focusing on LIP trauma further show that levels of violence peak where elevation is highest and most heterogenous. In other words, violence is greater in high elevation locations with variable topography relative to other high

Table 1. Results of bivariate and multivariate GLMs. Models with (LIP) listed in the response only include LIP trauma samples. The interactions column specifies models with interaction terms. Model estimates are converted from logit scale to probabilities.

Model	Response	Predictor(s)	Interactions	Prediction Test	Deviance Explained	Estimate	Std. Error	*t* value	*P*-value
1	Gen. trauma	Mean elev.	None	**P1**	**3.9**	0.5	0.0002	1.015	0.31955
2	Gen, trauma (LIP)	Mean elev.	None	**P1**	**27.8**	0.5001	0.0002	2.485	0.0225
3	Gen. trauma	SD elev.	None	**P2**	**21**	0.501	0.0014	2.611	0.0148
4	Gen. trauma (LIP)	SD elev.	None	**P2**	**31.4**	0.5001	0.0013	2.877	0.01
5	Gen. trauma	Latitude	None	**P3**	**0.2**	0.5024	0.0411	0.231	0.819
6	Gen. trauma	Mean elev.	* Period	**P1**	**38.6**	0.4996	0.0005	−3.159	0.0042
			MH			0.9537	0.9883	3.06	0.0054
			LIP			0.5001	0.0002	2.498	0.0198
7	Gen. trauma	SD elev.	* Period	**P2**	**24.6**	0.5012	0.0079	0.628	0.5357
			MH			0.1158	2.6803	−0.759	0.4555
			LIP			0.5009	0.0014	2.536	0.0181
8	Gen. trauma	Latitude	* Period	**P3**	**5.6**	0.4121	0.3161	−1.124	0.2720
			MH			0.0039	4.8746	−1.138	0.2660
			LIP			0.504	0.041	0.388	0.7010
9	Gen. trauma (LIP)	Mean + SD	None	**P1 + P2**					
		Mean elev.	None		**44**	0.5001	0.00018	1.785	0.0911
		SD elev.	None			0.5007	0.0013	2.004	0.0603
10	Gen. trauma (LIP)	Mean elev.	* SD elev.	**P5**	**58.2**	0.50	<0.0001	2.342	0.0316

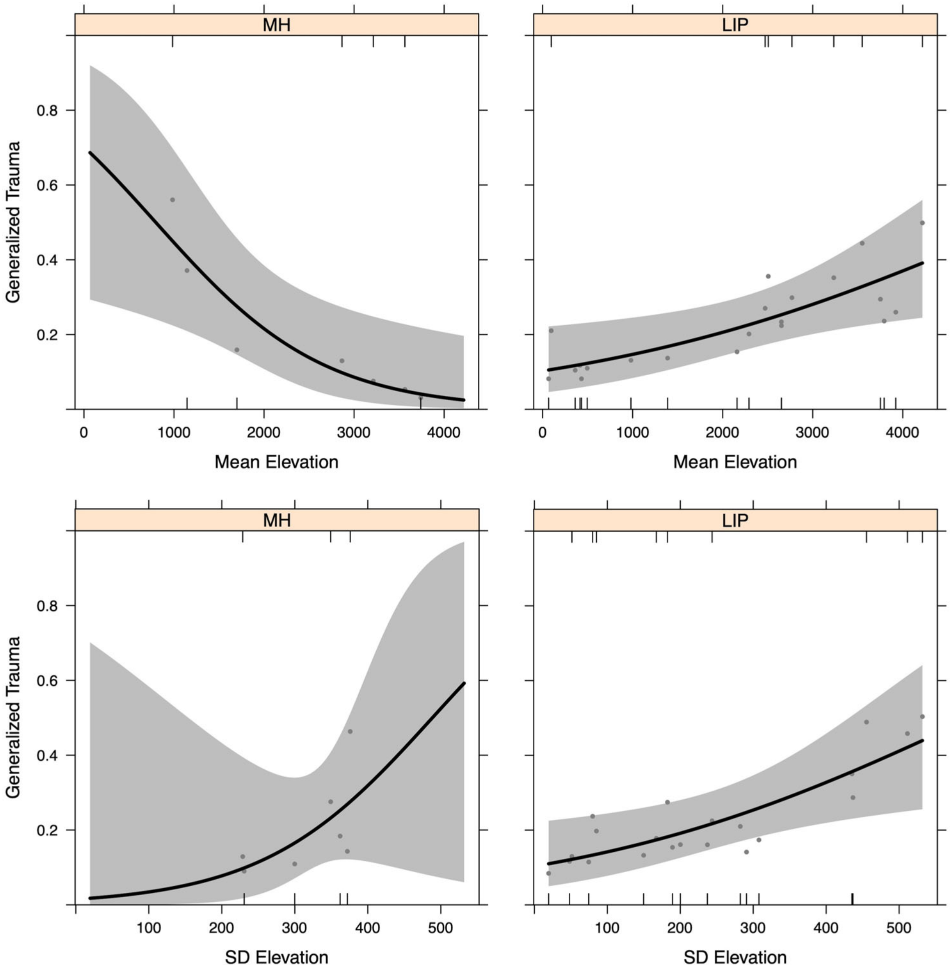

Figure 4. Partial response plots of the General linear models (GLM) comparing mean elevation (top row) and SD elevation (bottom row) to generalized trauma with time period as an interaction term. Black ticks denote trauma observations, points denote partial residuals, MH = Middle Horizon period (left panels), LI*P* = Late Intermediate period (right panels).

elevation regions with more homogenous terrain (Figure 5). Model results show no consistent relationship between latitude and violent trauma.

Discussion and Conclusion

Pastoralism and Violence. Model results most strongly support P5, with violence peaking in high elevation locations with heterogenous topography where environmental characteristics are most variable. Proportions of violent trauma increase along elevation influenced environmental gradients where risk-reducing agropastoral and field-scattering strategies were most common. However, this connection holds only for the LIP, when regional autonomy was highest, and breaks down during the MH when the Wari and Tiwanaku states controlled or influenced much of the central highlands. The difference in trends by time period suggests that periods of strong inter-regional connections either a) foster subsistence strategies less connected to local ecology (Toyne et al. 2017; Wilson and McCool forthcoming; Williams and Melissa 2013), with the result in this case that violent mortality is subdued or b) have institutions directly suppressing violent behaviors, potentially through coordinated punishment of violent actors (D'Altroy 2014; Kellner 2002; Torres-Rouff and Costa Junqueira 2006). During the LIP when regional autonomy is high there is a greater reliance on local ecology such that marginal, heterogeneous environments constrain the effective deployment of violence avoidance tactics, the result being greater numbers of casualties during episodes of violence and warfare. The high intensity of violence during the LIP may also relate to the increasing emphasis on high-elevation settlement and agropastoral economies during the LIP (Bauer and Kellett 2010; Parsons, Hastings, and Matos 1997), which would have further increased the costs of violence avoidance.

Table 2. ANOVA *P*-values show results for comparisons between the bivariate and multivariate models using a Likelihood Ratio Test (LRT). The first row compares differences in fit for models 2 and 9, the second row compares models 2 and 9 to model 10.

LRT ANOVA	Residual Deviance	Deviance	*P*-value
mod2~mod9~mod10	2.1002	0.60537	0.013
	1.5665	0.5336	0.0197

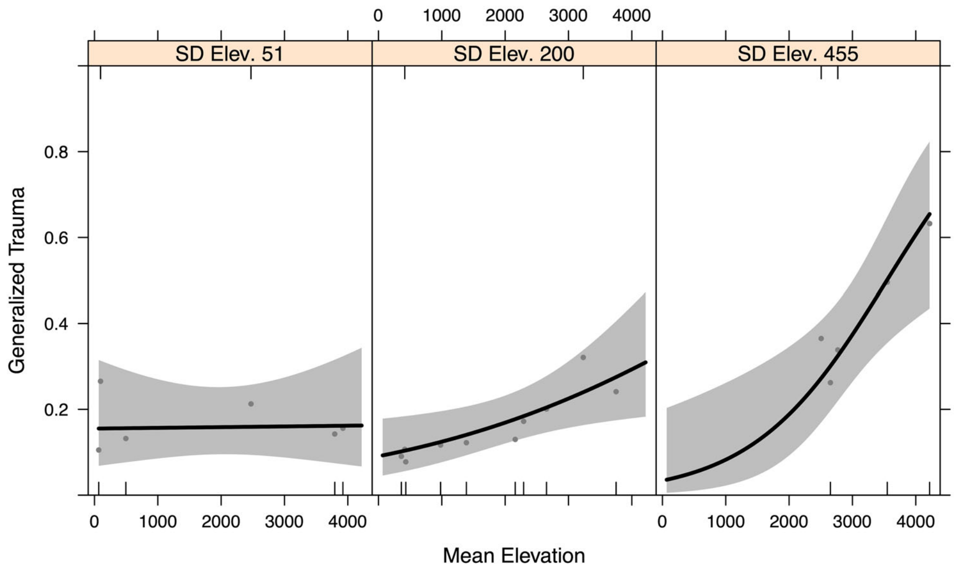

Figure 5. Partial response plots of the General linear model (GLM) comparing generalized trauma during the LIP with mean elevation and SD elevation as interaction terms. Cross-sections are plotted at the 10th, 50th, and 90th quantiles of SD elevation and show that the effect of mean elevation on generalized trauma becomes stronger as SD in elevation increases.

The significant negative co-variance between mean elevation and trauma during the MH suggest an interesting reversal of environmental effects during periods of imperial integration. The trend may reflect declining imperial control as one moves towards the coast and away from the imperial capitals located in high elevation locations. This may suggest a spatial pattern of increased likelihood of violence on the periphery of centralized political spheres that is reduced nearer the center (Andrushko and Torres 2011; Scaffidi and McCool 2021). Alternatively, this trend may simply be the result of non-local dietary and economic inputs in Wari and Tiwanaku controlled highland regions and the spread of the Pax-Wari to regions that experienced chronic warfare during the subsequent LIP. Whatever the reason, it appears that periods of greater sociopolitical integration led to lower rates of violence in the central highlands and may have prevented or suppressed the need for violence avoidance strategies altogether. Nonetheless, the small MH sample size renders these interpretations tentative, and will require the publication of larger datasets for more thorough testing.

The lack of a significant relationship between latitude and violence is puzzling, as latitude should influence variation in subsistence strategy (Winterhalder and Thomas 1978) and attendant violence exposure. The lack of a significant latitudinal trend is possible for several reasons: (1) the decreasing amount of pasturage as one travels north may incentivize territorial contests over increasingly scarce grazing habitat that equilibrate with more southern latitudes where increased reliance on herding renders violence avoidance strategies less effective. The result may be that these differing pathways lead to high (and similar) rates of violence in both low and high latitudes. (2) The increasingly marginal conditions of the southern altiplano may result in larger territory sizes and lower population densities to cope with low productivity and stochastic conditions. This may result in the creation of buffer zones between competing groups that disincentivize intergroup violence and raids and reduce contact in contested territories. The more productive conditions in northern latitudes may permit shorter travel times to viable grazing habitat while promoting higher population densities that push competing groups into proximity, thus reducing warning times and incentivizing conflict. These conditions may balance rates of violence between these disparate latitudes. Another possibility is that the decreased productivity in southern latitudes combined with larger territories could render theft and raiding less productive than simply producing (e.g. maintaining a herd, planting fields, etc.) – especially compared to the northern latitudes. Greater raiding travel times in combination with uncertainty regarding when and where raiding targets will be located may reduce the payoffs to the point where production might yield benefits that at times outweigh those of raiding.

Conclusion. The goal of this paper is not to explain the entire range of variation in rates of violence in the ancient Andes, but rather, to test whether environmental conditions that promote high subsistence mobility and seasonal population dispersal impact rates of violence via their imposition of higher costs on violence avoidance tactics. Our research shows that high elevation locations with variable topography exhibit the highest rates of generalized violence. These results support predictions that marginal and variable ecological conditions promote risk-reducing subsistence economic strategies that increase one's exposure to interpersonal violence by limiting the capacity for avoiding violence. This study shows that environmental influences on the costs of violence avoidance tactics are an important component of explaining variability in rates of violence. Additionally, this study documents the significant potential for sociopolitical interconnectedness to have mediating effects on violence, suggesting increasing complexity may reduce the likelihood of individuals experiencing interpersonal violence even in areas where violence avoidance is costly. While certainly numerous other factors influenced the rise and fall of violence in the Andes, most importantly the causal motivations for proactive violence, this study shows that rates of violence can be significantly affected by ecological constraints on violence avoidance tactics – a topic that should be explicitly considered in studies of prehistoric violence and its variable manifestations.

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Weston C. McCool is Postdoctoral Fellow in the Department of Anthropology at the University of Utah. I am interested in all the ways human beings adapt to challenging circumstances. Whether it be resource-poor environments, climate change, population pressure, or conflict, humans establish innovative, though not always successful, strategies for coping with hard times. My role as an archaeologist is to use our material remains to infer past behavior within a perspective of human ecology and evolution. This means I am interested in the archaeological record for what it can tell us about human behavior in relation to their social and ecological context and the forces of evolution. I am particularly interested in why humans so often resort to violence rather than cooperation. I explore this topic by investigating what conditions consistently lead to violence through a cost/benefit analysis, predicting that violence will arise when individuals think the expected payoffs outweigh the anticipated costs.

Kurt M. Wilson is a quantitative evolutionary ecologist and anthropologist whose research interests focus on human-environment interactions broadly, with a particular emphasis on the socioecological dynamics around the emergence and persistence of inequality, territoriality, cooperation, and ecological resiliency in human populations. To explore the complex dynamics within human-environment interactions, his work employs individual/agent-based modeling, big data, and statistical modeling to understand how local environments impact the payoffs and constraints individuals face. Kurt has field experience in the Central Andes and Western North America and has worked on Andean, Western North American, and global datasets.

Kenneth B. Vernon my research explores variation in human behavior within the framework of behavioral ecology. Currently, I am using geographic and spatial modeling techniques to investigate the nexus of climate, conflict, and human migration in the prehistory of the American Southwest. In addition, I am working to advance data management and data science in archaeology.

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