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# Does Wealth Predict Health Among Dogs in a Protected Area?

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## Abstract

As the world's most ubiquitous carnivore, domestic dogs maintain unique proximity to human populations. Partly because dogs potentially serve as hosts of zoonotic diseases, determinants of canine health are increasingly the focus of interdisciplinary research. Emerging perspectives suggest that dogs' health may vary as a function of their owners' wealth and financial resources, a correlation that could potentially inform public health programs and conservation efforts. The objective of this study was to evaluate associations between household wealth and the health of domestic dogs ( $n = 208$ ) among indigenous Mayangna communities in the Bosawás Biosphere Reserve, Nicaragua. The dogs were evaluated using serum biochemistry, complete blood count, and physical exam findings. Using these data, a principal components analysis (PCA) determined the presence of four "syndromes": 1) decreased body condition score (BCS) & hypoalbuminemia; 2) lymphocytosis & eosinophilia; 3) segmented neutrophilia; and 4) lymphadenopathy, tick infestation, & hyperglobulinemia. An inventory of possessions indexed household wealth. For all four syndromes, household wealth was a weak and uninformative predictor of the dogs' health. The few differences seen among dogs from households with different degrees of wealth likely reflect that nearly all dogs had marginal health and all households were relatively poor. Results from this study imply that owners' wealth may have diverse effects on canine health in rural settings.

**Keywords** Canine health · Socioeconomic status · Mayangna · Neotropics · One health · Nicaragua

## Introduction

In recent years, there has been growing recognition of the interconnectedness of health among humans, domestic and wild animals, and the environment (Zinsstag *et al.*, 2011). This "One Health" perspective advocates for increased

interdisciplinary research to elucidate the human and social dimensions of the health of animal populations (Gibbs, 2014). As the world's most common pet, domestic dogs maintain close proximity to humans and often serve as hosts for infectious diseases (Cleaveland *et al.*, 2000; Fiorello *et al.*, 2006; Gompper, 2014). The health of dogs in rural communities is potentially affected by multiple variables, including the wealth of their human companions (López *et al.*, 2009). In a pioneering study of 78 dogs in rural Panama, Fung *et al.* (2014) reported that dogs in wealthier communities are healthier than dogs from poorer communities. More recently, poverty has been cited as a potential risk factor for disease prevalence among dogs in Brazil and Argentina (Curi *et al.*, 2016; Enriquez *et al.*, 2019).

In terms of mechanisms, it is not necessarily clear how wealth affects the health of dogs. A limitation of previous research is that analyses have focused on community-level variation in wealth. It is worth noting, however, that correlations among higher-level units can be misleading (Kievet *et al.*, 2013). In other words, worse health among dogs in poorer communities does not necessarily imply that

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individual dogs in poorer households are in worse health than dogs who reside in wealthier households. To substantiate that latter relationship, studies are needed in which health is evaluated as a function of household wealth. Motivated by the community-level analysis of Fung *et al.* (2014), this report provides novel data on the correlation between household wealth and dogs' health. We are mindful that "health" is potentially a multidimensional construct. Therefore, we employ clinical insights and data reduction techniques to identify salient dimensions among the measures we used to evaluate health.

The study site is the Bosawás Biosphere Reserve in north-eastern Nicaragua, the centerpiece of one of the world's most extensive remaining rain forests (Stocks, 2003). Inhabited by indigenous Mayangna and Miskito horticulturalists, this study site provides a compelling context to investigate the effects of wealth on health. Although most households are impoverished by global standards (Winking *et al.*, 2018), there is considerable variability in wealth among the households in terms of their material wealth (Koster, 2018). Among the human population, household wealth predicts variation in dietary quality and childhood growth (Perri *et al.*, 2019; Winking & Koster, 2015). In terms of animal care, there are multiple ways that high household wealth could result in better health among dogs. For instance, wealthy families may have greater food security, resulting in more consistent and higher quality provisioning of dogs. Wealth might also provide discretionary income for the purchase of medications to treat dogs that need care.

In this paper, our focus is on the correlation between dogs' health and the wealth of their owners. In the One Health literature, practitioners acknowledge the importance of considering wealth and poverty as predictors of disease risks and other health considerations in relatively poorer settings (Cleaveland *et al.*, 2017; Thumbi *et al.*, 2015). A better understanding of the correlation between human wealth and canine health can promote improved interventions and public health policies to benefit both species (Costa *et al.*, 2018; Wallace *et al.*, 2017), and may have implications for research and policies that impact the wildlife species living in close association with humans and dogs (Knobel *et al.*, 2014).

## Materials and Methods

### Study Site

The Bosawás Biosphere Reserve comprises a humid lowland forest located in north-central Nicaragua. Together with neighboring protected areas of Honduras, it constitutes the largest protected area of Neotropical forest north of the Amazon basin (Smith, 2001). The reserve is inhabited by indigenous Mayangna and Miskito horticulturalists,



**Fig. 1** A domiciles in the Bosawás Reserve (photograph courtesy of James Liu)

who maintain putative territories (Stocks, 2003; Sylvander, 2018). Despite the gradual erosion of their territorial land rights, the Mayangna and Miskito remain relatively isolated (Hayes, 2007). At the time of data collection in July 2014, there were few roads into the indigenous communities, which also lacked civic plumbing, electricity, and cellular phone service (Fig. 1).

Virtually all Mayangna and Miskito households maintain agricultural plots, and local food production strategies also include hunting and fishing (Cooper *et al.*, 2018). Individuals acquire material wealth via diverse economic strategies, including artisanal gold panning, short-term wage labor, and mercantilism (Koster *et al.*, 2013). In the absence of banks and other financial institutions, families invest their money in possessions that serve to store wealth. It is common to invest in livestock, particularly cows and pigs, to be sold to external merchants (Koster, 2007). It is also common for families to invest in items that entail moneymaking opportunities or mercantilism, including chainsaws and outboard motors. Luxury items in this setting include gasoline-powered generators, inverters, and television sets with videocassette recorders.

Dogs in the Bosawás Reserve are distinguished by their prominent role in subsistence hunting, particularly by detecting and pursuing large rodents, armadillos, collared peccaries, and tapirs (Koster, 2006, 2008a). However, only a minority of dogs excel as hunting companions, and some dogs serve primarily as household companions and watchdogs (Koster & Tankersley, 2012). There is unambiguous ownership of dogs in this setting, and families give names to their dogs (Fig. 2). The dogs sleep in their owners' residences, and much of their time is spent in or around their owners' homes.<sup>1</sup> Dogs are provisioned by their owners,

<sup>1</sup> The second author's qualitative observations of dog behavior are complemented by quantitative research on the time allocation of dogs (Koster & Tankersley, 2012). These observations indicate that dogs



**Fig. 2** Dogs and their owners in the Bosawás Reserve (photograph courtesy of James Liu)

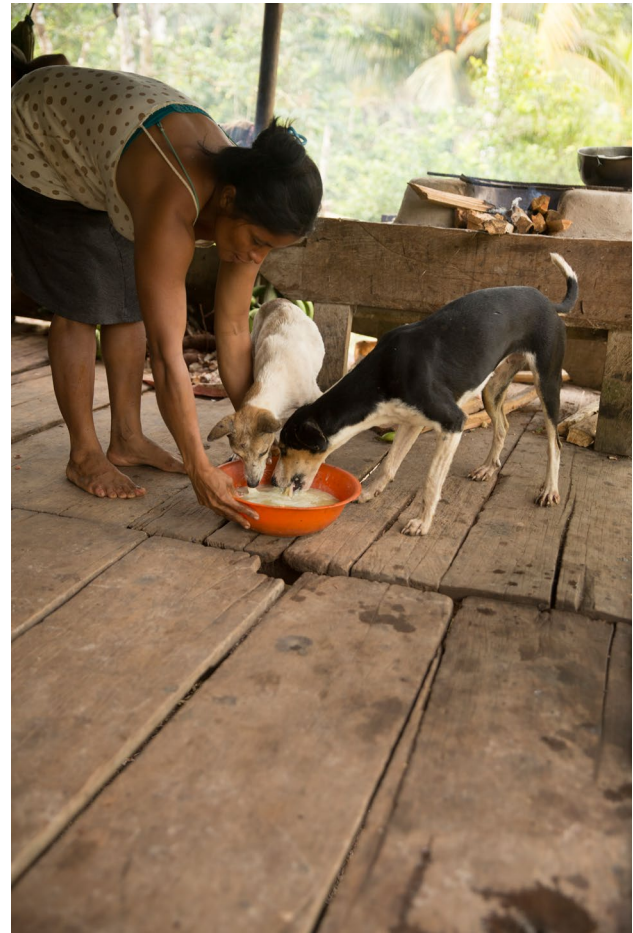
who provide food that has been prepared for family members (Fig. 3). Reflecting that provisioning, a stable isotope analysis of hair samples from dogs indicates that dogs' diets from the same household are relatively highly correlated (Tankersley & Koster, 2009). Dogs rarely scavenge alone beyond the community boundaries (Koster & Noss, 2014). The use of latrines reduces chances for coprophagy reported in other communities (Butler *et al.*, 2018).

As in comparable rural settings, dogs in the Bosawás Reserve receive minimal veterinary care (Koster, 2009). Except for rabies vaccinations administered by transient groups of government workers, vaccinations are generally rare. Medications are not altogether absent, however. Circulated through mercantile networks, oxytetracycline and ivermectin are typically available for purchase and recognized as remedies for bacterial infections and parasitic infections, respectively. Nevertheless, previous veterinary evaluations of this population suggest that virtually all dogs are nutritionally compromised and carrying a heavy infectious disease burden, including exposure to canine distemper virus, canine parvovirus, and leptospirosis (Fiorello *et al.*, 2017). Parasitic infections are common, such as Chagas disease (Roegner *et al.*, 2019; Vogel *et al.*, 2018). Mortality rates are high, and most dogs die by the age of six years old (Koster & Tankersley, 2012).

The research took place in four communities in the Bocay River watershed: Ahsa Was, Amak, Pulu Was, and Wina (Fig. 4). These communities vary in population size and proximity to settlements outside the indigenous territories.

Footnote 1 (continued)

spend the majority of their daylight hours in the domiciles of their owners or on day trips to horticultural plots or other locations with their owners. These data also include observations of provisioning by the dogs' owners. There were no observations of dogs eating foods other than those provided by their owners.



**Fig. 3** Dogs are provisioned by their owner in the Bosawás Reserve (photograph courtesy of Debra Bardowicks)

In these communities, we estimate that approximately 70% of the households own at least one dog (see also Perri *et al.*, 2019).

### Recruitment of Dogs

Our objective in each community was to assess every dog and collect data from its human guardian. Upon arrival at each community, we met with local leaders to explain the purpose of our study and to request permission to collect the data. Community leaders typically encouraged participation among villagers, although their participation was strictly voluntary. Dog guardians were compensated approximately 1 US dollar per dog that they brought to participate in the project. A total of 250 dogs were enrolled in the study, though 42 were juveniles and excluded from the sample presented here.<sup>2</sup> The sex ratio was

<sup>2</sup> Juveniles were distinguished on the basis of their dentition (Czupryna *et al.*, 2016).



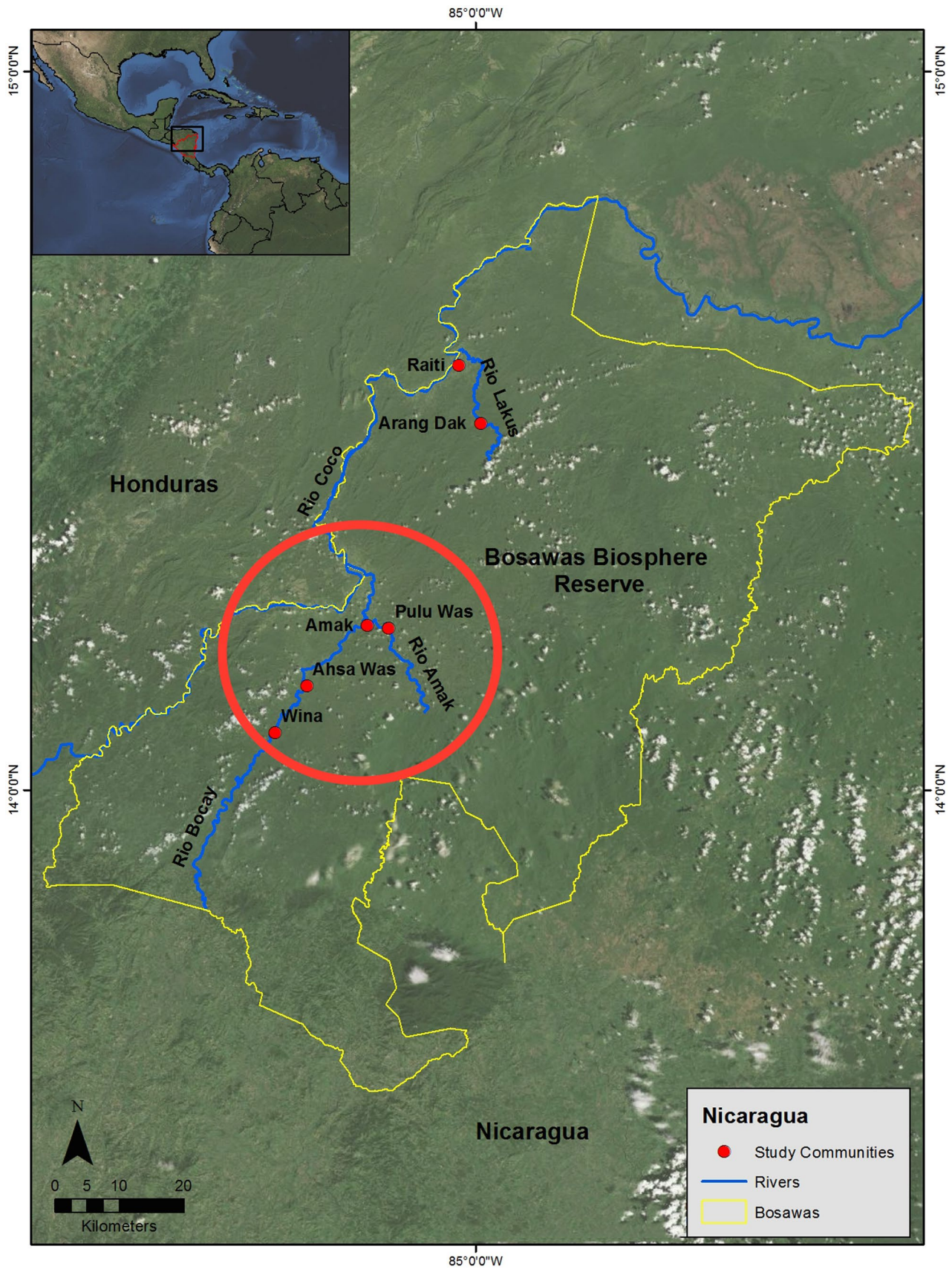


Fig. 4 Map of the four study communities in the Bosawás Biosphere Reserve in north-central Nicaragua: Ahsa Was, Amak, Pulu Was, and Wina

approximately balanced, with 103 male (49.5%) and 105 female (50.5%) adult dogs. We anticipate that we sampled at least 90% of the dogs that resided in the study communities.

## Household Wealth Survey

With help from a local interpreter, owners were surveyed for background information on their dogs and the material possessions of their households ( $N = 124$ ). The data collection focused on the possession of critical assets that distinguish the wealth of households, such as rifles, radios, flashlights, electric generators, cows, and pigs. Each household's measure of wealth in Nicaraguan córdobas was the sum across all high-value goods of the quantity owned of each item multiplied by its prevailing market rate in the mestizo towns surrounding the reserve. The use of material possessions as an indicator of household wealth is commonly used by anthropologists working in rural, relatively poor communities (Borgerhoff Mulder & Beheim, 2011; Ross *et al.*, 2018). In addition to the distinguishing assets mentioned above, all households maintain a limited supply of staple possessions, including cookware and clothing. To incorporate the material value of these possessions, we assume that a constant value of 500 Nicaraguan córdobas serves as the baseline wealth for households in this sample.

Despite their geographical differences, the range of wealth in the four study communities overlapped considerably (Table 1). In this study, although there is relatively minimal variation between communities, there is substantial heterogeneity of household wealth within the whole sample. For instance, some participants from the largest study community owned no valuable possessions, whereas some of the wealthiest owned possessions equivalent to approximately \$13,000. The distribution of material wealth was positively

**Table 1** Summed monetary value of essential household possessions ( $N = 124$  dog-owning households) in 4 predominantly Mayangna communities in the Bosawás Biosphere Reserve, Nicaragua. Values are reported in Nicaraguan córdobas (NIO). At the time of data collection in 2014, the exchange rate was approximately 26 córdobas per US\$1. Households were also assumed to have essential possessions worth an additional 500 córdobas, which was added to the values reported here and then log-transformed as the measure of household wealth used in the analysis

| Village  | N   | Mean (SD)         | Median | Minimum | Maximum |
|----------|-----|-------------------|--------|---------|---------|
| Ahsa Was | 13  | 59,946 (89,890.3) | 29,000 | 500     | 332,300 |
| Amak     | 69  | 49,396 (67,137.3) | 26,500 | 0       | 340,500 |
| Pulu Was | 15  | 29,907 (34,896.6) | 17,500 | 1000    | 132,000 |
| Wina     | 27  | 44,144 (71,484.5) | 22,500 | 500     | 333,500 |
| Combined | 124 | 47,001 (67,508.2) | 25,000 | 0       | 340,500 |

An ANOVA model reveals no significant community-level differences in wealth among participating households ( $F = 0.596$ ,  $p = 0.618$ )

skewed, so we log-transformed this variable before the statistical analysis.

Among the households that participated in the study, the median number of adult dogs owned by the household was two dogs (ranging from a minimum of one dog to a maximum of four dogs). The number of dogs in these households did not correlate with our measure of household wealth.<sup>3</sup>

## Physical Examinations

Each dog was muzzled and manually restrained for physical examination and sample collection by veterinary students under the direct supervision of a veterinarian. A 9-point body condition score (BCS) scale was used, with 1 = emaciated, 5 = ideal, and 9 = morbidly obese, and any dog with a score  $< 4$  is considered underweight (Laflamme, 1997; Bowland *et al.*, 2020). The BCS scheme uses parameters such as fat cover over ribs, presence of abdominal tuck, and fat stores over the hips to assess nutritional status. Lymphadenopathy was scored as 0 = no enlargement, 1 = uni- or bilateral enlargement of 1 pair of lymph nodes, 2 = uni- or bilateral enlargement of 2 pairs of lymph nodes, etc. for mandibular, prescapular, axillary, inguinal, and popliteal lymph nodes. Each dog received a tick infestation score for attached ticks: 0 = no ticks, 1 = 1–3 ticks, 2 = 4–6 ticks, 3 = 7–9 ticks, or 4  $\geq 10$  ticks.

## Sample Collection and Processing

Blood was collected from the jugular or cephalic vein into serum separator and ethylenediaminetetraacetic acid (EDTA) tubes. The microhematocrit tubes were centrifuged for 3 min at 5000 rpm for the determination of packed cell volume (PCV). Total solids were measured by refractometry. Blood smears were stored in a microscope slide box with silica gel packets to minimize humidity. After centrifugation of serum separator tubes at 5000 rpm for 10 min, sera were pipetted into cryotubes and stored in liquid nitrogen until arrival in the United States, where they were stored at  $-80$  °C until analysis.

## Serum Chemistry Analysis and Hematology

Before analysis, serum samples were allowed to thaw at room temperature. Approximately 100  $\mu$ l of serum were placed into a freshly opened VetScan reagent rotor cartridge

<sup>3</sup> We assessed this relationship by fitting a Poisson generalized linear mixed model with an observation-level random effect to account for possible overdispersion. The effect of log-transformed household wealth was an uninformative predictor of the number of dogs owned by the households ( $\beta = 0.04$ ,  $SE = 0.04$ ).

**Table 2** Distribution of physical examination scores and hematologic values for 18 health variables from dogs (N=203) from the Bosawás Biosphere Reserve, Nicaragua. For each variable, the number of dogs whose values for a given variable fell within a given bin is shown.

| Variable               | N   | Very Low | Low             | Normal              | High              | Very High | -       |
|------------------------|-----|----------|-----------------|---------------------|-------------------|-----------|---------|
| BCS*                   | 203 | 108      | 70              | 25                  | -                 | -         | -       |
| PCV                    | 175 | 16       | 64              | 95                  | -                 | -         | -       |
| Total solids           | 174 | -        | -               | 25                  | 125               | 24        | -       |
| Albumin*               | 191 | 18       | 69              | 104                 | -                 | -         | -       |
| BUN*                   | 188 | -        | 68              | 119                 | 1                 | -         | -       |
| Globulin               | 191 | -        | -               | 157                 | 26                | 8         | -       |
| Phosphorus*            | 192 | -        | 20              | 164                 | 8                 | -         | -       |
| Sodium*                | 187 | -        | 40              | 145                 | 2                 | -         | -       |
| Segmented Neutrophils* | 196 | -        | 56              | 132                 | 8                 | -         | -       |
| Banded Neutrophils*    | 196 | -        | -               | 175                 | 19                | 4         | -       |
| Lymphocytes*           | 199 | -        | 3               | 163                 | 32                | 1         | -       |
| Monocytes*             | 197 | -        | 14              | 178                 | 5                 | -         | -       |
| Basophils*             | 197 | -        | -               | 118                 | 62                | 17        | -       |
| Platelets              | 157 | -        | 6               | 59                  | 63                | 29        | -       |
| Variable               | N   | Normal   | Mildly Elevated | Moderately Elevated | Markedly Elevated | -         | -       |
| Eosinophils*           | 198 | 124      | 56              | 9                   | 9                 | -         | -       |
| Variable               | N   | None     | Mild            | Moderate            | Marked            | -         | -       |
| Leukocyte Toxicity     | 201 | 147      | 35              | 17                  | 2                 | -         | -       |
| Variable               | N   | Score=0  | Score=1         | Score=2             | Score=3           | Score=4   | -       |
| Tick Infestation*      | 208 | 115      | 45              | 24                  | 14                | 10        | -       |
| Variable               | N   | Score=0  | Score=1         | Score=2             | Score=3           | Score=4   | Score=5 |
| Lymph-adenopathy*      |     | 42       | 101             | 54                  | 8                 | 1         | 0       |

BCS body condition score, PCV packed cell volume (see text for definitions)

and analyzed for albumin, blood urea nitrogen (BUN), globulin, phosphorus, sodium alkaline phosphatase (ALP), alanine aminotransferase (ALT), total bilirubin, creatinine, glucose, amylase, calcium, potassium, and total protein using a VetScan® VS2 serum chemistry analyzer as directed by the manufacturer (VetScan VS2 Operator's Manual, 2009).

Blood smears were stained using a modified Wright-Giemsa solution and examined under light microscopy to estimate counts of white blood cells, segmented neutrophils, band neutrophils, lymphocytes, monocytes, eosinophils, basophils, and platelets. The degree of leukocyte toxicity (none, mild, moderate, & marked) was recorded for each blood sample. Platelet counts were estimated by averaging ten platelet counts per high-powered field. Many slides had clumping of platelets precluding assessment, leaving only 157 slides that could be evaluated for platelets. A board-certified veterinary clinical pathologist was consulted when needed to interpret slides accurately.

## Analysis

We employed a multi-stage analytical strategy to test for the effects of household wealth on dogs' health. One challenge is

Variables were binned into 3 or 4 categories based on published reference ranges. Those variables marked with an asterisk were included in the final principal components analysis

that there is no widely accepted measure of "health," and it is certainly a multifactorial construct. That is, individual dogs can be healthy in some ways and simultaneously unhealthy in other ways. Just as medical practitioners rarely use a single metric to make a diagnosis, we chose to use a combination of physical exam findings and clinical pathologic findings to assess health.

Body condition scores were binned into 3 categories: very low (BCS ≤ 2), low (BCS = 2.5–3.5), and normal (BCS ≥ 4). Packed cell volume, total solids, and counts of total leukocytes, neutrophils, bands, lymphocytes, monocytes, eosinophils, and basophils were binned based on reference intervals published in the Merck Veterinary Manual (2015b), and platelet counts were binned based on a reference range published by Veterinary Information Network (Smith & Warren, 2015) (Tables 2 and 3). The serum chemistry values were binned based on ranges published in the manufacturer's manual of the serum chemistry analyzer (VetScan VS2 Operator's Manual, 2009). Hematologic and biochemical analytes were tested for normality using the Shapiro–Wilk Test for Normality ( $p < 0.05$ ).



**Table 3** Reference ranges and bin ranges for values of 5 serum chemistry analytes from 193 domestic dogs in the Bosawás Biosphere Reserve, Nicaragua. Each variable was divided into 3 clinically relevant ranges to create categorical variables

| Analyte (unit)              | Reference range | Very Low | Low     | Normal  | High    | Very High |
|-----------------------------|-----------------|----------|---------|---------|---------|-----------|
| Albumin (g/dl)              | 2.5–4.4         | < 1.7    | 1.8–2.3 | > 2.4   | -       | -         |
| Blood urea nitrogen (mg/dl) | 7–25            | -        | < 6     | 7–24    | > 25    | -         |
| Globulin (g/dl)             | 2.3–5.2         | -        | -       | < 5.2   | 5.3–6.0 | > 6.0     |
| Phosphorus (mg/dl)          | 2.9–6.6         | -        | < 2.9   | 3.0–6.6 | > 6.7   | -         |
| Sodium (mmol/L)             | 138–160         | -        | < 137   | 138–160 | > 161   | -         |

Principal component analysis (PCA) was conducted using a subset of binned variables from the physical exam, hematologic, and serum chemistry values. Most of the individual analytes and metrics are not diagnostic on their own but must be interpreted in the context of other findings and diagnostic tests. As a method for reducing the dimensionality of multivariate data, PCA can be used to identify clusters of correlated variables (Dunteman, 1989). Disease states tend to result in predictable patterns of abnormalities. We used PCA to identify clusters among variables that might relate to specific disease states that were known or likely to be present among Bosawás dogs. We call these disease states "syndromes" to distinguish them from specific diagnoses one might give an individual patient.

Visual evaluation of the PCA identified four clusters of clinically relevant variables, and each of these clusters was subsequently used to define a syndrome. Individual dogs were then assigned to a syndrome if they met all of that syndrome's criteria. Dogs were then categorized with a binary outcome variable according to their values on the evaluative measures.

After dogs were categorized as meeting the criteria for the syndrome or not, these outcomes were iteratively modeled as a function of household wealth using logistic regression models in a generalized estimating equations (GEE) approach to account for the pseudoreplication of dogs from the same household.

## Results

### Physical Examinations

Key health variables are summarized in Table 2. Most dogs were skinny; the mean BCS was 2.5 out of 9 (SD = 0.96, N = 203), and the median was 2.0. Typically, one or more lymph nodes were enlarged, resulting in a mean lymphadenopathy score of 1.2 (SD = 0.80, N = 206) and a median

of 1.0. The median number of ticks found on dogs was 0, although we observed at least one tick on 44.7% of the dogs and at least ten ticks on 4.8% of the dogs.

### Serum Chemistry Analysis and Hematology

Results from 14 serum chemistry parameters were recorded from 193 dogs. Based on reference ranges and bin definitions in Table 3, the summary of values for these dogs is presented in Table 4. Albumin, calcium, and glucose values tended to be lower than the reference range. Alanine aminotransferase (ALT) values tended to be slightly higher than the reference range, and the remaining analyte values were mainly within the reference ranges.

Packed cell volume (PCV) was determined for only 175 dogs because 33 tubes were lost or broken during processing; from these samples, the mean PCV was 35.4% (SD = 6.8), and the median was 36%. Total solids was determined for 174 samples; the mean was 8.6 g/dl (SD = 0.9), and the median was 8.4 g/dl. Both PCV and total solids were normally distributed and within reference ranges.

Differential leukocyte counts from the blood smears are shown in Tables 5 and 6. Notably, although the means of these variables were generally within the reference range, eosinophil, basophil, and platelet counts tended to be slightly higher than the reference range. We note that four blood smears had neutrophils containing morula-like structures, making them suspect for active *Ehrlichia* spp. infections. Microfilariae from the heartworm *Dipetalonema reconditum* were identified on one smear.

### Principal Components Analysis

Five serum chemistry variables were considered for inclusion in the PCA: albumin, BUN, globulin, phosphorus, and sodium. Alkaline phosphatase (ALP) was excluded because of its lack of organ specificity and the possibility of age-related confounding (Center, 2015). Alanine aminotransferase (ALT),



**Table 4** Reference ranges (RR) and means of 14 serum chemistry analytes from 193 dogs from the Bosawás Biosphere Reserve, Nicaragua. The number of dogs with values of a given analyte falling below, within, or above the RR is shown. Those analytes marked with an asterisk were included in the final principal components analysis

| Analyte (unit)                 | Reference Range | N   | Mean (SD)      | <RR | Within RR | >RR |
|--------------------------------|-----------------|-----|----------------|-----|-----------|-----|
| Albumin* (g/dl)                | 2.5–4.4         | 191 | 2.42 (0.484)   | 87  | 104       | -   |
| Alkaline phosphatase (U/L)     | 20–150          | 192 | 75.3 (47.36)   | 9   | 171       | 12  |
| Alanine aminotransferase (U/L) | 10–118          | 193 | 37.7 (12.72)   | -   | 191       | 2   |
| Amylase (U/L)                  | 200–1200        | 193 | 668.5 (169.37) | -   | 192       | 1   |
| Total bilirubin (mg/dl)        | 0.1–0.6         | 191 | 0.25 (0.051)   | -   | 191       | -   |
| Blood urea nitrogen* (mg/dl)   | 7–25            | 188 | 9.1 (5.35)     | 68  | 119       | 1   |
| Calcium (mg/dl)                | 8.6–11.8        | 188 | 9.76 (1.190)   | 15  | 169       | 4   |
| Phosphorus* (mg/dl)            | 2.9–6.6         | 192 | 4.57 (1.201)   | 20  | 164       | 8   |
| Creatinine (mg/dl)             | 0.3–1.4         | 190 | 0.80 (0.241)   | 3   | 186       | 1   |
| Glucose (mg/dl)                | 60–110          | 193 | 64.2 (21.94)   | 92  | 97        | 4   |
| Sodium (mmol/L)                | 138–160         | 187 | 141.1 (6.45)   | 40  | 145       | 2   |
| Potassium (mmol/L)             | 3.7–5.8         | 191 | 5.58 (1.256)   | 20  | 164       | 8   |
| Total protein (g/dl)           | 5.4–8.2         | 193 | 6.77 (1.036)   | 19  | 165       | 9   |
| Globulin (g/dl)                | 2.3–5.2         | 191 | 4.35 (0.927)   | -   | 157       | 34  |

total bilirubin, and creatinine were excluded as there was minimal variation, and most dogs had values within the reference range. Glucose values tended to be low, likely due to ex vivo cellular consumption during storage. Amylase was excluded

because of nonspecificity and unclear clinical correlations. Despite there being some abnormal values, calcium and potassium were excluded because of a lack of variation.

**Table 5** Hematology reference ranges and bin definitions for packed cell volume (PCV), total solids, and leukocyte counts among domestic dogs (N=193) from the Bosawás Biosphere Reserve, Nicaragua. Each variable was divided into 3 or 4 clinically relevant categories to create binned variables

| Variable (Unit)             | Reference Range | Low    | Normal      | High            | Very High     |
|-----------------------------|-----------------|--------|-------------|-----------------|---------------|
| PCV (%)                     | 35–57           | < 34   | 35–57       | > 58            | -             |
| Total solids (g/dl)         | 5.4–8.2         | < 5.3  | 5.4–8.2     | > 8.3           | -             |
| Leukocytes (/ul)            | 5000–14,100     | < 4999 | 5000–14,100 | > 14,101        | -             |
| Segmented neutrophils (/ul) | 2900–12,000     | < 2900 | 2901–12,000 | > 12,001        | -             |
| Banded neutrophils (/ul)    | 0–450           | -      | < 450       | 451–1000        | > 1000        |
| Lymphocytes (/ul)           | 400–2900        | < 400  | 401–2900    | 2901–5400       | > 5400        |
| Monocytes (/ul)             | 100–1400        | < 100  | 101–1400    | > 1401          | -             |
| Basophils (/ul)             | 0–100           | -      | < 100       | 101–300         | > 300         |
| Platelets (/HPF)            | 8–20            | < 8    | 9–20        | 21–32           | > 32          |
| Variable (Unit)             | Reference Range | Normal | Mildly High | Moderately High | Markedly High |
| Eosinophils (/ul)           | 0–1300          | < 1300 | 1301–2200   | 2201–3100       | > 3100        |

**Table 6** Estimated differential cell counts from blood smears of domestic dogs (N=200) from the Bosawás Biosphere Reserve, Nicaragua. Those variables marked with an asterisk were included in the final principal components analysis

| Hematologic value (unit)     | Reference range (RR) | N   | Mean (SD)     | <RR | Within RR | >RR |
|------------------------------|----------------------|-----|---------------|-----|-----------|-----|
| Leukocytes (/ul)             | 5000–14,100          | 200 | 9061 (5265.7) | 52  | 126       | 22  |
| Segmented neutrophils* (/ul) | 2900–12,000          | 196 | 4907 (2962.2) | 56  | 132       | 8   |
| Banded neutrophils* (/ul)    | 0–450                | 198 | 165 (394.9)   | -   | 175       | 23  |
| Lymphocytes* (/ul)           | 400–2900             | 199 | 1730 (1097.8) | 3   | 163       | 33  |
| Monocytes* (/ul)             | 100–1400             | 197 | 462 (372.8)   | 14  | 178       | 5   |
| Eosinophils* (/ul)           | 0–1300               | 198 | 1163 (791.6)  | -   | 124       | 74  |
| Basophils* (/ul)             | 0–100                | 197 | 462 (327.8)   | -   | 118       | 79  |
| Platelets (/HPF)             | 8–20                 | 157 | 23 (11.0)     | 6   | 59        | 92  |

Total protein was excluded because it was expected to be highly correlated with albumin, globulin, and total solids.

The following 18 binned variables were included in the initial PCA: BCS, tick infestation score, lymphadenopathy score, PCV, total solids, segmented neutrophils, banded neutrophils, lymphocytes, monocytes, eosinophils, basophils, platelets, leukocyte toxicity, albumin, globulin, BUN, sodium, and phosphorus. For each of these variables, values  $\geq 3$  standard deviations from the mean were excluded from the analysis. To simplify the parameter space and analysis while maximizing the number of dogs incorporated into the dimension reduction analysis, four variables were removed prior to the final PCA: PCV, total solids, platelets, and leukocyte toxicity. The rationale for removing PCV and total solids was the small sample sizes. Platelets were excluded because they were commonly clumped, which likely resulted in inaccurate counts. Leukocyte toxicity was removed because it had high co-linearity with the segmented neutrophil count. Once these variables were removed, data from 159 individual dogs remained, and the 14 included variables were rotated (oblimin with Kaiser normalization) and reduced to two extracted components. These two components, with eigenvalues greater than 1.5 (1.941 and 1.819), cumulatively explained approximately 27% of the total variance.

The variables were plotted by both components in rotated space and four principal syndromes were determined visually based on a combination of their clinical significance and the clustering of variables (Fig. 5). The syndromes included 1) Hypoalbuminemia and low BCS, indicating nutritional stress; 2) Eosinophilia and lymphocytosis, consistent with parasitism or other chronic inflammation causes; 3) Neutrophilia, consistent with acute inflammation; and 4) Hyperglobulinemia, ticks present, and lymphadenopathy, consistent with tick-borne disease. Case definitions were

subsequently created for each of the four syndromes of sick dogs using binned values for each given variable (Table 7).

### Household Wealth as a Predictor of Health

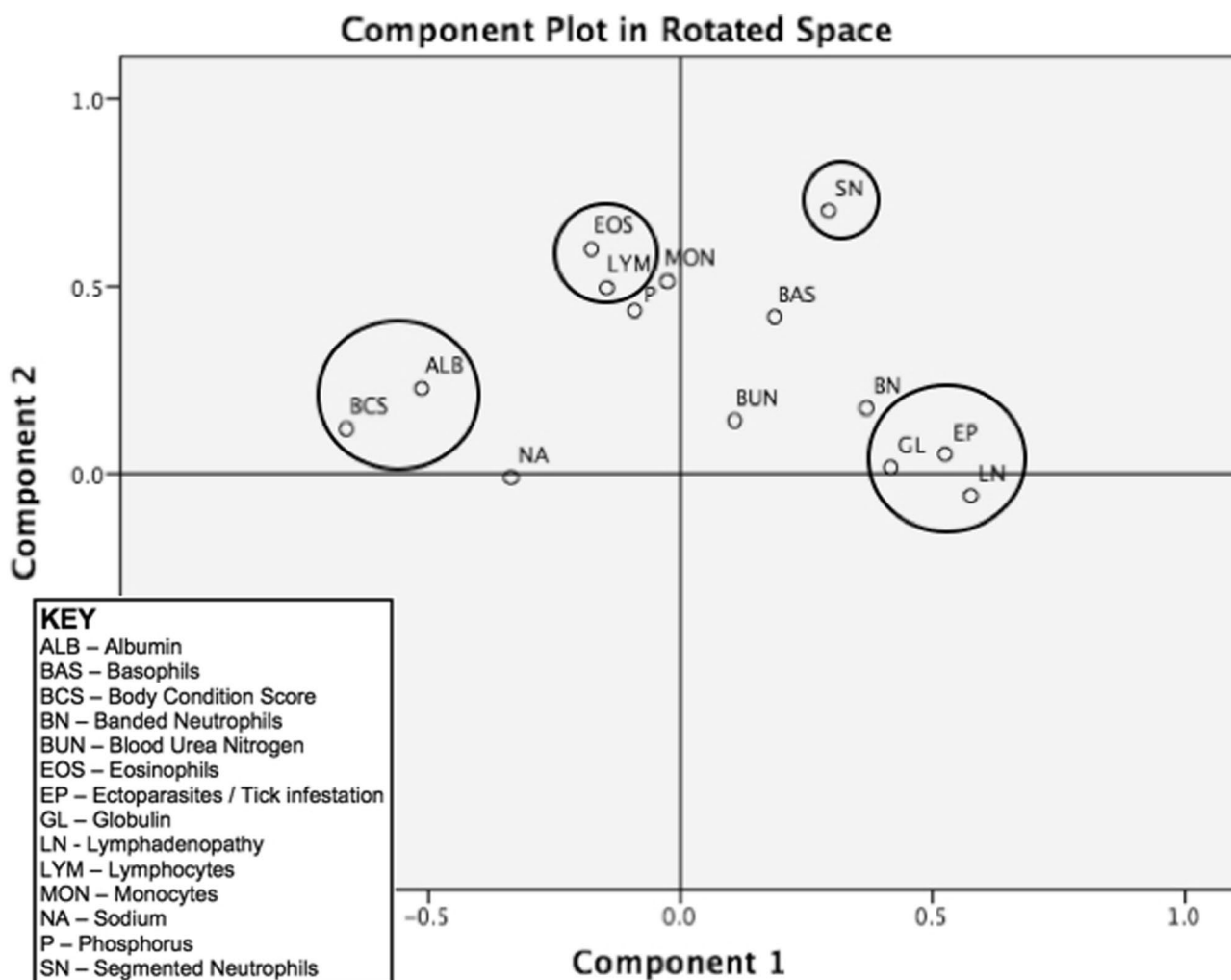
For all four syndromes, household wealth was a weak and uninformative predictor of the dogs' health (Table 8). In other words, the hypothesis that dogs in wealthier households exhibit superior health was not supported. It is possible that other predictors, such as the age and sex of the dogs, might explain variation in health. However, we do not anticipate that statistical models including such variables would show a more pronounced effect of wealth as a predictor.

## Discussion

### Wealth as a Predictor of Health

There is a seemingly minor relationship between household wealth and dog health in the study population of dogs in the indigenous territories of the Bosawás Reserve. This result provides a complementary perspective to Fung *et al.*'s (2014) research, who reported that dogs in wealthier Panamanian communities are healthier than dogs in poorer communities. The results of the present study suggest that the effects of wealth on canine health show variability across socio-ecological contexts, with between-community variation potentially more germane than within-community variation. In other words, the causes of variation in canine health are likely to differ substantially in rural international settings, and the wealth of the dogs' owners is unlikely to exhibit consistent effects.

The reasons for the lack of an effect of wealth in the Bosawás Reserve are speculative. It is noteworthy, however,



**Fig. 5** Fourteen health parameters of hunting dogs from the Bosawás Biosphere Reserve incorporated into final principal components analysis (PCA) and plotted by two extracted components in rotated

(oblumin) space. Circles encompass the variables that were used to define four clinically relevant syndromes for subsequent analysis

**Table 7** Case definitions for four diseases “syndromes” of dogs from the Bosawás Biosphere Reserve, Nicaragua. Each row indicates which variables were included, and the columns represent the binned values of the variables incorporated into each syndrome case definition. Sam-

ple size information shows the number of dogs who exhibited the syndrome as a proportion of the total sample size for that syndrome. Sample sizes vary across syndromes because of heterogeneous missingness in the variables

| Variable              | Syndrome #1<br>Nutritional stress<br>(N = 81/187) | Syndrome #2<br>Parasitism<br>(N = 5/196) | Syndrome #3<br>Acute inflammation<br>(N = 8/195) | Syndrome #4<br>Tick-borne<br>disease<br>(N = 9/188) |
|-----------------------|---|--|--|---|
| BCS                   | Low or very low                                   | -  | -  | -   |
| Albumin               | Low or very low                                   | -  | -  | -   |
| Eosinophils           | -   | Moderately elevated or markedly elevated | -  | -   |
| Lymphocytes           | -   | High or very high                        | -  | -   |
| Segmented Neutrophils | -   | -  | High   | -   |
| Tick infestation      | -   | -  | -  | Score<br>1, 4, 7, or 10                             |
| Globulin              | -   | -  | -  | High or very high                                   |
| Lymphadenopathy       | -   | -  | -  | Score<br>2, 3, 4, or 5                              |



**Table 8** Generalized estimating equation (GEE) estimates of syndromes as a function of log-transformed household wealth for dogs in the Bosawás Biosphere Reserve. Parameter estimates are presented

| Parameter              | Syndrome 1      | Syndrome 2      | Syndrome 3      | Syndrome 4      |
|------------------------|-----------------|-----------------|-----------------|-----------------|
| Intercept              | 0.573 (1.092)   | − 1.110 (2.194) | − 2.065 (2.216) | − 2.749 (1.686) |
| Household wealth (log) | − 0.089 (0.107) | − 0.257 (0.225) | − 0.110 (0.221) | − 0.024 (0.164) |

on the log-odds scale (robust standard errors in parentheses). An exchangeable correlation structure was specified to account for the pseudoreplication of multiple dogs from the same household

that variation in household wealth does not correlate with the quality of dogs' diets. Whereas wealthier humans in this setting consume relatively higher-quality diets, a stable isotope analysis on a nearby sample of dogs and humans found that this correlation is not apparent among dogs (Perri *et al.*, 2019). In general, it seems that household wealth is a poor indicator of household investments in dogs. The original hypothesis was that the costs of maintaining healthy dogs are marginally lower for wealthier families – logic that potentially explains the high investments in dogs and other pets in industrialized settings (Gray & Young, 2011; Gray *et al.*, 2015). Alongside the costs of keeping dogs, however, it is also worth considering the benefits. The assistance of skilled hunting dogs in this setting can be substantial, resulting in large quantities of meat that can be consumed, traded, or sold (Koster & Leckie, 2014; Koster, 2008b). Among relatively low-income families, such benefits might incentivize them to invest marginally more effort in the care of their dogs. For wealthier families with ample alternatives, the marginal benefits of having dogs may be relatively minor, essentially lowering the incentive to invest.<sup>4</sup> A previous study in this setting examined nutritional indicators as a function of dogs' hunting ability and found no effect. However, the sample size was small and did not consider the effects of wealth as a possible moderator (Koster & Tankersley, 2012). To evaluate such possibilities, more research is needed on the specific ways that households invest in their dogs and how these behaviors potentially co-vary with wealth. There are also important opportunities to examine cultural variation in norms of ownership and care, which potentially differ for reasons not considered in the present analysis (Gray & Young, 2011; Chambers *et al.*, 2020; Koster, 2021).

### Health as a Multidimensional Construct

Veterinary evaluations of dogs in rural settings like the Bosawás Reserve are rare, and this study provides additional evidence that dogs in this setting frequently exhibit relatively poor health. In this study, we asserted that health is

a multidimensional construct, and we endeavored to define syndromes based not only on the PCA but also on their clinical significance. For instance, most dogs had very low BCS, and this low BCS clustered on PCA with hypoalbuminemia, which we interpreted as nutritional stress (syndrome 1). Of all dogs sampled, 45.5% had hypoalbuminemia, reflecting decreased protein synthesis, increased protein loss, and/or decreased protein intake. For this dog population, decreased synthesis or increased loss seem less likely than poor intake given the universality of subnormal body condition.

Syndrome 2 was defined as eosinophilia and lymphocytosis, which were seen in 37.4% and 16.6% of tested dogs, respectively. Many dogs also had basophilia. These findings are commonly associated with parasitism and chronic inflammation. These dogs are potential carriers of endoparasites such as *Toxocara canis*, *Ancylostoma caninum*, *Trichuris vulpis*, *Taenia* spp., and *Dipylidium caninum* (Robertson & Thompson, 2002). Chronic inflammation can have many disparate causes, which may explain the lack of relationship with household wealth. Young animals may have higher concentrations of circulating lymphocytes (Greeley *et al.*, 2001), but animals younger than six months of age were excluded from the study. Other causes of chronic inflammation, such as neoplasia, are less likely in this population of young adult dogs. Therefore, Syndrome 2 can be interpreted as chronic parasitism severe enough to result in inflammatory changes.

Segmented neutrophilia, which defined Syndrome 3, was evident in 4% of the dogs and was likely associated with acute inflammation or stress response, and less likely, epinephrine-induced excitement or neoplasia. Acute inflammation may be associated with infectious illnesses such as gastroenteritis, bacterial pneumonia, hepatitis, or injuries, such as those incurred during hunting. Neutrophilia is expected for a finite period in the early stages of illness or injury, thus explaining its association with acute disease. Few dogs would be expected to have neutrophilia at any time since most will have progressed to chronic disease or recovered. The rarity of Syndrome 3 in our sample, therefore, makes sense. For this analysis, Syndrome 3 can be interpreted to indicate acute inflammation caused by disease or injury.

The final syndrome is defined as the presence of ticks, elevated serum globulin, and lymphadenopathy. The mild lymphadenopathy seen in many dogs was likely due to

<sup>4</sup> Such arguments are conceptually analogous to the growth-defense tradeoff and the predicted effects of resource availability (Coley *et al.*, 1985).

chronic immune stimulation from ectoparasites, endoparasites, and infectious disease agents. One-fifth of dogs were hyperglobulinemic, consistent with chronic antigenic stimulation and, notably, suspected *E. canis* infection. While most dogs did not have any ticks, 45% had at least one tick on them. According to information provided by the interviewees, there are more ticks in the dry season (February–May) than the rainy season; we sampled in July at the height of the rainy season. Also, dogs without ticks may have been infected by ticks that had already dropped off at the time of the exam. There were four suspect *Ehrlichia canis* cases on blood smears, and previous research has found a high seroprevalence to the tick-borne bacteria *Rickettsia rickettsii* (87%) and *Ehrlichia* spp. (37%) among Bosawás dogs (Fiorello *et al.*, 2017). Ticks are ubiquitous in study communities, especially in the forest; dogs that venture into the forest will almost certainly acquire ticks. Syndrome 4 can therefore be interpreted as a tick-borne disease.

In addition to abnormalities grouped by PCA into the four syndromes, we also detected other hematological abnormalities, including anemia and thrombocytosis. Nearly half of the dogs were anemic, typically with minimal reticulocytosis and polychromasia, indicating that most anemias were non-regenerative. Causes of nonregenerative anemia in this population would be iron-deficiency secondary to ectoparasitism, and anemia of chronic disease in late-stage ehrlichiosis, and long-term malnutrition and intestinal helminthiasis. More than half of the dog's platelet counts were elevated, which could be explained by epinephrine-release during a physical exam or bone marrow disease. More likely, the thrombocytosis may be secondary to infection, inflammation, acute or chronic blood loss from parasitism, or tissue damage from physical trauma. Anemia is expected to be found with syndromes 1, 2, and 4, and depending on the specific injury or illness, syndrome 3. Unfortunately, due to technical problems, our sample size for PCV was small, so we excluded this parameter from our analysis.

## Conclusion

In summary, this study did not reveal a correlation between household wealth and canine health. This result may reflect the fact that nearly all dogs had marginal health and, despite pronounced wealth inequality within communities, the households nevertheless were relatively impoverished overall. Professional veterinary care in rural Nicaragua was mainly non-existent. In settings with a more extensive range of variation along these dimensions, the effects of wealth on health may be more pronounced. As One Health researchers consider the interconnectedness of human and animal populations, it is worth noting that variation in household wealth

and resources may entail diverse consequences in disparate socio-environmental contexts.

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## Declarations

**Ethics Statement** The animal study was reviewed and approved by the Institutional Animal Care and Use Committee of the University of California, Davis. Informed consent was verbally obtained from all participants, as many of the dog guardians were functionally illiterate. The authors have no conflicts of interest to declare that are relevant to the content of this article.

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