HYDRATION STRATEGIES, NUTRITION, AND HEALTH DURING A LIFESTYLE TRANSITION IN THE BOLIVIAN AMAZON

by

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(Under the Direction of Susan N Tanner)

ABSTRACT

This dissertation research investigated hydration strategies, hydration status, perceptions of the water environment, health, and nutrition among Tsimane' forager-horticulturalists undergoing lifestyle transitions in the Bolivian Amazon. Globally, 748 million people do not have access to clean drinking water. How humans meet their water needs through diet is critical to understand because it is extremely costly to make genetic changes or physiological adaptations when dealing with environmental constraints, like water scarcity. This dissertation adds to a human adaptation theoretical approach by examining water holistically within the diet and in relation to disease pressures. Specifically, it investigated water intake and hydration status, how different strategies were associated with gastrointestinal illness risk, how intakes and hydration levels compared to industrial populations, and how perception of water insecurity were related to health outcomes following a major flood in two rural Tsimane' villages in Beni, Bolivia. It combined ethnographic, nutritional, qualitative, anthropometric, and biomarker data to contribute to literatures on nutritional adaptations, human adaptability, water insecurity, and global climate change by examining human-environment interactions revolving around water use among a population undergoing lifestyle transitions. It demonstrated that hydration strategies that utilize high proportions of food for water are associated with lower risk of GI illness. These hydration strategies appear to serve as nutritional adaptations to minimize exposure to pathogens through lower intake of raw or untreated water. Findings illustrated that Tsimane' absolute water intake and intake from foods was significantly higher than international water recommendations. However, it also found that close to 50% of the individuals were dehydrated. Using random-effects regression models, it illustrated that differences in ambient temperature, activity patterns, and lifestyle drive daily rhythms of hydration. An unintended consequence of lifestyle transitions may be an increased vulnerability to dehydration. Finally, it extended the construct of water insecurity to a water rich, flood prone region and illustrated that high water insecurity was associated with an elevated risk of diarrhea for adults and that maternal medium and high water insecurity related to increased risk of dehydration for their children.

INDEX WORDS: Hydration, Human biology, Water intake, Heat Adaptation, Urine specific gravity, Water insecurity, Amazonia, Bolivia, Tsimane'

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TRANSITION IN THE BOLIVIAN AMAZON

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CHAPTER 1

INTRODUCTION

Research description

This dissertation research investigated hydration strategies, hydration status, perceptions of the water environment, health, and nutrition among Tsimane' forager-horticulturalists undergoing lifestyle transitions in the Bolivian Amazon. Research focused on the human biology of water intake, examining human water needs holistically from nutritional, evolutionary, and environmental perspectives. Specifically, I investigated water intake and hydration status, how different strategies were associated with gastrointestinal illness risk, how intakes and hydration levels compared to industrial populations, and how perception of water insecurity were related to health outcomes following a major flood in two rural Tsimane' villages in Beni, Bolivia. I combined ethnographic, nutritional, qualitative, anthropometric, and biomarker data to contribute to literature on nutritional adaptations, human adaptability, water insecurity, and global climate change by examining human-environment interactions revolving around water use among a population undergoing lifestyle transitions that closely interacts with its environment.

The search for safe water has been and continues to be a critical challenge facing humanity as approximately 748 million people lack access to improved water (WHO and UNICEF, 2014). How humans interact with and perceive their environment to meet their water needs is a key driver of behavior and health and disease. Behavioral strategies and choices to use a specific water source over others or to forego liquid sources of water for water substitutes, like foods or fruit, in response to environmental selection pressures may have played critical roles in the development of human traits like body size, or the decoupling of thirst from dehydration (Wheeler, 1993; Noakes, 2010). Extreme conditions including water scarcity, scarcity of clean water, hot-humid temperatures, and greater variability in climate in the 21st century will place added pressure on humans to meet water needs (Magrin et al., 2014).

Globally, many populations are experiencing rapid economic and environmental changes, including many in the South American Amazon region (Izquierdo, 2005; Hidalgo et al., 2014; Piperata et al., 2011; Welch et al., 2009). While the social sciences emphasize that lifestyle transitions, or changes to dietary, economic, and cultural activities, affect health and disease patterns, the role of dietary water use and hydration patterns have been widely overlooked during these transitions. Hydration strategies, or how people meet their daily dietary water needs through a full spectrum of foods and liquids, may serve as nutritional adaptations that balance nutrition, hydration, and risk of infection. Lifestyle transitions may create a mismatch between hydration strategies and the nutritional landscape. Many populations undergoing transitions frequently report symptoms of dehydration and these populations are expected to bear the brunt of the health outcomes associated with global climate change (Barkey et al., 2001; Izquierdo, 2005; Lundgren et al., 2013). This research will explain how hydration strategies are associated with pathogen exposure, how lifestyle and environmental differences affect daily patterns in hydration, and how perception of water insecurity is associated with health outcomes among Tsimane' Amerindians in lowland Bolivia, where access to clean water is scarce.

Responses to transitions are critical to understand because they provide insight into past and future trends of human variation in nutrition and health as people deal with environmental constraints (Aiello & Anton, 2013). The three research questions this dissertation attempts to address are: 1) How do humans without consistent access to clean water meet their water needs and how are hydration strategies used as tradeoffs to buffer stressors; 2) How does variation in ambient temperature, lifestyle, and physical activity affect daily hydration patterns during lifestyle transitions in a hot-humid environment; and 3) Do humans living in a water rich, yet clean water scarce environment perceive water insecurity and how do these perceptions map onto objective disease and nutrition patterns.

In addressing these questions, this dissertation will contribute to human adaptation theory within the hot, humid environment. It will address how humans respond to a hot, humid environment with little access to clean water through diet, behaviors, and physiology. Moreover, it will discuss how these behaviors buffer stressors and the implications for tradeoffs between thermoregulation, hydration, and gastrointestinal disease. This dissertation will inform water intake recommendations, which rely almost exclusively on data from industrialized countries. It will also inform about potential nutrition and disease health outcomes of global climate change as findings presented on weather and hydration levels can be extrapolated to evaluate how rising temperatures and increased variability may affect human physiology and adaptability. Overall, the aim of this dissertation is to advance our knowledge of water intake patterns in extreme ecological conditions among a population undergoing rapid change with limited access to clean water.

Field site

I chose the Tsimane' territory in lowland Bolivia to conduct this research because it is a hot-humid, water-rich, yet clean water-scarce environment. The hot-humid environment raises a key dilemma in the human physiological response to heat, namely the reduced effectiveness of sweat evaporation to cool the body (Hanna and Brown, 1983). Interestingly, most of the adjustments to humid heat are behavioral and cultural rather than physiological (Moran, 2008). For example, villages are built on a rise of ground near a water source. Minimal clothing allows for maximum skin surface available for sweat evaporation and either open or closed housing is used to cool or warm insides. Behavior follows a pattern to reduce exposure to heat with work beginning in the early morning, midday rest followed by moderate work (Moran, 2008). Yet, the combination of a lack of access to clean water, a lack of electricity to control climate, and high physical activity levels on a day-to-day basis make Tsimane' an ideal population to study human water needs, water-related behaviors, and perceptions of water quality and quantity.

The Tsimane' territory lies 50 km east of the Andean foothills, approximately 14°5' south to 15°5' south latitude and between 66°5' and 67°5' west longitude. This region is located in the lowland department of the Beni, one of nine departments in Bolivia. The majority of Tsimane' villages are on the banks or tributaries of the Maniqui River. The climate is characterized by high, stable average temperatures (26.8 °C average yearly temperature), high humidity, and high rainfall (1,743 mm mean rainfall) (Godoy et al., 2008). The year is split into two distinct seasons. The dry season lasts from May to October, while the wet season occurs from November to April. Tsimane' have access to six main water sources, including the river, streams, ponds, and in closer villages to San Borja they have access to wells, covered hand pump wells, and a couple of communities have piped water that provide cleaner water, as well as the option of collecting rain water.

During the course of the fieldwork for this dissertation, exceptionally heavy rains between December 2013-February 2014 produced a historic flood in the southwestern Amazon. January and February of 2014 were the rainiest months on record since the beginning of observations in 1944 at three different sites in the Beni (Espinoza et al., 2014). A rain station in

Rurrenabaque, which is close to the Tsimane' territory, recorded 1100 mm of rain in under three weeks, between January 24th and February 10th, which is more than 63% of the average annual rainfall in the region (Godoy et al., 2008). The flood in the Beni, Bolivia was declared a national emergency by the Bolivian government on February 4th, 2014. The majority of Tsimane' villages had standing water for between seven and 28 days. Villages downriver from the central city of San Borja had standing water for longer periods than communities upriver from San Borja because they are at lower elevations. The flood largely subsided by the end of February upriver, but downriver, the flood changed the path and ecology of the Maniqui River. This resulted in shallower water that created several other short-term flooding events (1-3 days) due to heavy rains. Conditions remained challenging until early April in the downriver villages.

The duration and severity of the flood produced large property and food losses. The majority of the plantain, manioc, and rice crops, as well as planted fruits in the slash and burn horticultural fields or small gardens died due to standing water that rotted the crops. Water sources were also affected as at least one covered hand-pump well fell into the river through the erosion of the riverbank where the pump had been placed. Tsimane' who lived in villages close to San Borja were either evacuated to San Borja, the nearby market town, where they stayed in refugee camps at local school shelters, or they retreated deep into the forest to higher ground. At the refugee camps, the San Borja mayor's office collaborating with the local San Borja hospital and local aid groups provided them with food, shelter, water, and medical care. Helicopters with food aid were sent out on non-rainy days to close-by villages. In villages far from San Borja, Tsimane' primarily retreated deep into the forest, or built bunks within their houses to be above the flood waters, and little aid was delivered to them. Reports stated that the helicopter food delivery only reached as far upriver as Yaranda, a village that is a full day's travel away from San Borja.

The Bolivian Amazon is known for heavy rainy seasons, yet this unanticipated flood provided an opportunity to examine water insecurity in a previously unexplored way. While floods are known to affect water quality and risk of diarrheal diseases (Brouwer et al., 2007; Luby et al., 2008), previous studies of water insecurity have primarily examined this construct within water scarce environments (Stevenson et al., 2012; Wutich & Ragsdale, 2008). Water-rich environments full of dirty water, especially during flood conditions, present different challenges, yet challenges that affect the multiple dimensions of water insecurity, including access, adequacy, and lifestyles.

Chapter objectives

Chapter 2 provides a brief review of three areas of literature concerning human water needs. I start by reviewing adaptations in mammals to water scarcity. I then review human water needs from a nutritional and biocultural perspective, examining water recommendations and drawing examples from dietary studies examining behavioral and dietary adaptations and interactions with the environment to meet water needs. I then examine human adaptation and the human biology of hydration and thermoregulation by discussing physiological and behavioral adaptations to hot environments. I close by discussing water insecurity and its connections to health outcomes. By framing water as a critical resource necessary for survival and reproduction, chapter 2 demonstrates that the perspective of human adaptability can be closely aligned with water insecurity as multiple water environments can create the perception of water insecurity. I rely on these three bodies of literature for the body of the dissertation in chapters 3, 4, and 5.

The objective of Chapter 3 is to explore human flexibility in water consumption as a nutritional adaptation. Specifically, this chapter examines hydration strategies of Tsimane', compares them to international water references, and tests how hydration strategies, particularly water from food is associated with gastrointestinal illness. While a host of literature in anthropology has examined how humans meet their protein and other macronutrient needs, much less has evaluated how humans meet their water needs. Using logistic regression analysis, it demonstrates that hydration strategies that utilize high proportions of food for water are associated with lower risk of GI illness as a way to minimize exposure to pathogens through lower intake of raw or untreated water. This chapter also shows that cultural perceptions of clean water fall along organoleptic, or sensory, perceptions of clear and turbid and smelly or not. It also discusses the potential of reverse causality bias and how GI illness may affect hydration strategies through restriction of intake. Finally, to assess how closely water recommendations match onto intake of a population living in a hot-humid environment, it illustrates that the water intake from foods and absolute intake of this sample of Tsimane' is significantly higher than international water recommendations.

Chapter 4 examines human adaptability to the hot-humid environment through hydration patterns. Utilizing focal follow, anthropometric, urine, and ambient temperature data over a five-month period, this chapter examines the predictors of hydration status within the context of lifestyle transitions. Many populations undergoing lifestyle transitions report symptoms of dehydration, yet changes in environment and lifestyle have been overlooked in regard to hydration and instead research has focused on implications for disease patterns and body weight (Baker et al., 1986; Cordain et al., 2005; Popkin, 1994). Each individual in the sample provided two sets of measurements, which allowed for testing of how urine specific gravity, a biomarker of hydration status, changes within individuals over the course of a day. Using random-effects regression models, I illustrate that differences in lifestyle through village membership, ambient temperature, and activity patterns drive daily rhythms of hydration. Individuals living in a close community more integrated into the market economy were significantly more dehydrated than individuals living in a distant community. This chapter contributes to human adaptability literature by indicating that many types of environmental pressures, like humid heat, and not just water scarcity, may have played key roles in developing adaptations like voluntary dehydration and decoupling thirst from hydration as ambient temperature is tightly linked to hydration status (Noakes, 2010; Hanna & Brown, 1983). Finally, by examining villages at opposite ends of the spectrum to market exposure, this chapter adds the health effect of dehydration to the list of health consequences of lifestyle transitions.

The objective of Chapter 5 is to examine how individual perceptions of water insecurity following a major flood are associated with environmental and community attributes, and in turn, how water insecurity is related to the two most salient health outcomes associated with a lack of access to clean water, diarrhea and dehydration. First, using data from semi-structured interviews, participant observations, and previous water and food insecurity studies, I locally adapted a water insecurity questionnaire before the flood occurred. Second, I used a survey with exhaustive sampling in both communities to collect data on water insecurity, health outcomes in combination with a doctor exam, anthropometrics, water quality analysis, and urine specific gravity. I discuss individual reports of water behaviors in response to the flood to understand how floods may affect different dimensions of water insecurity. Using tobit regression models, I illustrate that the predictors of water insecurity are primary water source, age, and village membership. Second, using logistic regression models, I show that categories of high water insecurity is associated with an elevated risk of diarrhea for adults compared to adults who have low water insecurity and that maternal medium and high water insecurity relate to increased risk of dehydration for their children in comparison to children whose mothers have low water insecurity. This chapter extends the body of literature pertaining to water insecurity in two ways. First, it extends the concept of water insecurity to a post-flood water-rich, yet clean water scarce environment. Second, while previous research has linked water insecurity with mental health outcomes and anxiety (Ennis-McMillan, 2001; Hadley & Wutich, 2009; Stevenson et al., 2012; Wutich & Ragsdale, 2008), this chapter shows that water insecurity is also related to water related diseases including diarrhea and dehydration (Wutich & Brewis, 2014).

Chapter 6 provides a summary of the findings from the analyses presented in chapters 3-5. I summarize the dissertation's main findings and discuss the implications for the three studies presented in the dissertation to nutritional adaptations and flexibility in meeting human water needs, international water recommendations, and global climate change in regard to projected hotter temperatures and increased frequency of major floods.

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CHAPTER 2

LITERATURE REVIEW: THE EVOLUTION OF HUMAN WATER NEEDS, HYDRATION AND THERMOREGULATION, AND PERCEPTION OF THE WATER ENVIRONMENT

Introduction

Water is the main limiting factor for human survival (Finlayson, 2014). The process of homeostasis with water, thirst, and hydration is a critical process that is constantly in flux. Unlike camels, humans have not evolved to store water efficiently (Noakes, 2010). Instead, humans use diet, behavior, culture, technology, and physiological adaptations and accommodations to regulate water needs and hydration (Frisancho, 1993). While humans are a very widely adapted species living in virtually every ecological niche on earth with local adaptations and use different strategies to extract enough water to survive, Lieberman (2015:99) states that "all human populations are variants of a basic adaptive pattern for long-term aerobic exertion in hot habitats." Many other animals (e.g., desert mice) are narrowly adapted to fill specific niches (MacMillen & Lee, 1967; MacMillen et al., 1972; Koford, 1968).

In this chapter, I review literature covering cross-cultural variation in human water needs from nutritional anthropology, adaptations to heat and its influence on hydration status and fluid balance, and perceptions of water as a resource using water insecurity literature. However, I begin with a comparison of human to other animal adaptations to water scarcity to understand inter- and intraspecific variability in physiology, function, and plasticity in responses to different ecological conditions.

Mammals are unique animals in that they only have kidneys to osmoregulate, or keep homeostasis of an organism's water and salt balance. Many other vertebrates, including reptiles, birds, and fish, have other extrarenal functions to remove salt and other excreta without water loss (Beuchat, 1990a). Yet, for mammals, the kidney can meet an incredible variation of dietary and environmental demands through phenotypic plasticity resulting in structural and functional modifications (Beuchat, 1990a). The loop of Henle in the nephron is what is responsible for increasing the concentration of urine in the kidney through countercurrent multiplication, where the urine becomes more concentrated as it moves deeper into the medulla of the kidney (1990b).

However, an interesting allometric, or scaling, relationship exists governing the extent to which a mammal can concentrate its urine. Specifically, Beuchat (1990b; 1996) reports a strong negative correlation between body size and relative medullary thickness and maximum concentrated urine, such that the smallest mice and rodents can produce the most concentrated urine. This is observed through many desert mice that live in arid environments that are virtually exogenous water-free, meaning that they can persist for weeks with only dry food and no externally available water (MacMillen & Lee, 1967). It is a paradox as to why larger mammals do not have the same urine concentration ability as smaller mammals (Beuchat, 1990a), but one of the key confounders of the mammalian relationship between the kidney and the urine concentration ability is that the environment, aridity, diet, metabolism, and activity levels all affect this ability (Beuchat, 1996).

Adaptations to water scarce, or arid, environments have been examined in species from rats, to birds, to rabbits, to antelope to understand how these species adapt to extreme environments (Williams et al., 2001). The question of genetic adaptation versus phenotypic plasticity to different environments has been examined through urine concentrating ability, kidney function and morphology, and water turnover. Tate and Marco (2014) found that *Oryctolagus cuniculus* rabbits living at different South African islands with variation in aridity show phenotypic plasticity as rabbits display renal morphological adaptations (higher relative medullary thickness). These adaptations result in an increased ability to concentrate urine. Similarly, Tieleman et al. (2003) found that birds have a general adaptation to water scarcity in that their basal metabolic rate and total evaporative water loss decrease with increasing aridity. These adaptations would be favorable in water scarce environments because they would reduce dietary requirements and thermogenesis. In hot dry environments generating less heat and having a lower metabolic rate would reduce energetic expenditures and water turnover. However, an aridity gradient was not significantly associated with water turnover rate and urine osmolality for the Black-tailed Tree Rat *Thallomys*, suggesting a genetic basis and evolutionary adaptation to dry environments (Coleman & Downs, 2009).

While birds have general adaptations to water scarcity, they are also subject to dehydration and have behavioral adaptations to avoid water imbalance during migrations, such as flying at altitudes with more wind, not flying during the hottest parts of the day, seeking shade, and seeking water at stopover sites (Klaasen, 2004). Dietary preferences are also affected by exogenous water availability. Water availability significantly affected Blackcaps dietary preference during an experiment as water restricted birds switched to eating more water rich insects than fruit with lower water content (Tsurim et al., 2008). The finding that during periods of water stress, birds will choose to eat a diet filled with foods that are more water-rich than under normal conditions indicates an underlying attempt to reach water balance through dietary behaviors.

Additionally, water availability during migration at stopover sites affected how much food desert adapted birds consume depending on their winter habitat, such that if a bird is accustomed to extreme aridity, water availability at the stopover site is not as important to food consumption as for a bird that lives in a winter habitat with regular water availability (Sapir et al., 2004; Tsurim et al., 2008). The implications of this finding is that water availability in an ecological habitat during ontogeny and preceding generations influences dietary behaviors that may lead to success of completing long migrations as well as reproductive success. Therefore, the amount of available water in a species' habitat may directly influence dietary behaviors and program them to need certain amounts of water.

Water restriction, such as drought, during pregnancy and gestation results in lower birth weight in sheep and rats, but more importantly results in a higher plasma osmolality threshold for vasopressin secretion, which regulates retention of body water by concentrating urine in the kidney and conserves water (Ross & Desai, 2005). Recent experimental evidence shows a similar phenomenon among American Alligators when dehydration occurs during embryonic development as the physiological phenotype was significantly affected by reducing embryonic mass and baseline heart rate (Tate et al., 2012). This fetal programming, influenced by ecological conditions, indicates that extreme water restriction can contribute to phenotypic plasticity during development.

Similar evidence among humans sheds light on how humans are affected by water scarcity during development. Using weather patterns over a 20 year period in a semiarid region of Brazil, Rocha & Soares (2015) found that drought conditions, measured through rainfall, during human gestation and particularly the 2^{nd} trimester were significantly associated with higher infant mortality and child health problems than children who did not experience drought in utero (Rocha & Soares, 2015). Therefore, timing of exposure to different ecological conditions can have long-standing health and nutritional implications.

Variation in human water needs

A central research focus of nutritional anthropology is to understand how flexibility in diet serves as an adaptation to environmental constraints and is related to human variation in nutrition and health (Pelto et al., 2000; Stinson, 1992). Advances in nutritional anthropology have led to research examining inter-relationships between health, disease, nutritional status and dietary strategies especially during periods of rapid economic change (Pelto et al., 2000; Piperata et al., 2011; Welch et al., 2009). Nutritional anthropology often relies on an ecological framework to understand how diet buffers individuals and populations from multiple stressors (Haas & Harrison, 1977). Haas and Harrison (1977:71) describe a human adaptability approach to the study of nutrition:

> The adaptive strategy employed by the group is established in a feedback system that relies on such characteristics as the demographic structure of the group, the availability of vital resources, and the relative effect of the behavioral buffers to reduce the stress so that the usually more costly biological (genetic) adaptations need not be utilized. Within this model, nutrition may serve as a stressor in the form of a nutrient deficiency or as a vital resource in the human environment that is necessary to activate a behavioral or biological buffering system in response to other stresses.

Most nutritional anthropology and evolutionary research has emphasized how variation in protein, carbohydrate, and fat needs of humans affects growth, development, and nutrition (Cordain et al., 2000; Leonard, 2012; Lumey et al., 2007). There has been less attention to water as a macronutrient and how variation in hydration strategies affects health in humans

(Armstrong, 2012; Kleiner, 1999). This lack of attention is a problem because the majority of the data available comes from industrial populations

Thirst and drinking are biocultural processes driven by human evolution and physiology melded with local ecological conditions and cultural norms (Vargas, 2001). Obtaining enough water on a daily basis is critical to physiological and cognitive health (Murray, 2007), yet little cross-cultural research has documented which water sources people use to meet their hydration needs (Armstrong, 2012). Water is an essential nutrient comprising 40 to 65% of total body weight and is required in amounts beyond the body's ability to produce it (Jequier & Constant, 2010). According to the Institute of Medicine (IOM), the adequate intake levels (AIs), or experimentally derived values expected to meet the nutritional adequacy for moderately active individuals in a healthy population, for men and women are 3.7 liters (L) and 2.7 L daily, respectively (Food and Nutrition Board, 2004). The European Safety Food Authority (ESFA, 2010) recommends lower water intake at 2.5 L and 2.0 L for men and women based on European nutritional studies.

These values vary with body size, activity levels, metabolism, clothing, temperature, and pregnancy and lactating status (Sawka et al., 2005). These recommendations have been critiqued for not distinguishing between sources of hydration, e.g., between water from sugar-sweetened beverages and plain water, tea, and coffee as well as not emphasizing the water potential of foods (Popkin et al., 2006; Tsindos, 2012). Recently, research in nutrition has called for water intake in cross-cultural settings to substantiate the water intake AI recommendations (Armstrong, 2012).

Hydration strategies, or how a person meets his/her daily water needs through a full spectrum of foods and liquids, vary worldwide by local ecology and food culture (Nagata et al., 2011; Neumann et al., 1977; Paque, 1976). Humans obtain water from liquid sources (water and other beverages), food sources, and oxidation, or the water created through metabolic processes (~250 ml/per day) (Vivanti, 2012). Nutritional surveys in the United States, Europe, and Australia provide intake averages among industrialized populations. Kant and colleagues (2009) analyzed water intake in the adult U.S. population from the National Health and Nutrition Examination Surveys (NHANES). Using 24-hour multiple-pass diet recall, they found an average total water intake of 3.5 L and 2.9 L among men and women, with 33% coming from plain water, 48% coming from beverages, and the remaining 19% from food. A 1995 Australian national nutritional survey found similar total water intake values with males consuming 3.4 L and females 2.8 L; however, slightly more of the water was derived from food sources at ~25% (McLennan & Podger, 1998). A similar nutritional survey from Germany demonstrates lower total water intake values of 2.5 L and 2.1 L among men and women with food sources contributing ~29% of water intake (Manz et al., 2012).

In Latin America, research about hydration strategies has been scarce. Accurate data on water intake is rarely reported, but can be estimated from nutritional surveys or ethnographic accounts. Berti and Leonard (1998) analyzed dietary intake in Highland Ecuador and found that adult men and women consumed 2.6 L and 2.4 L of water with ~65% of water intake coming from water and milk and ~35% from tubers, grains, and fruits/vegetables. Kuna of Panama and Colombia have been reported to consume up to 0.9 L/day of a variety of cocoa-based drinks as their primary source of hydration (Chevaux et al., 2001), yet ethnographic research has contradicted these findings, pointing to several variants of *chicha* (a home-made fermented beverage) as more important sources of hydration (Howe, 2012).

Across Amazonia, fruits, tubers, and traditional fermented beverages are important components of hydration strategies likely because of limited access to clean water (Clement, 2006; McClatchey & Reedy, 2010). For example, the açaí palm's drupes (*Euterpe oleracea*) and coconuts are important sources of energy and hydration for Kayapo and Ribeirinhos of Brazil (Piperata et al., 2011; Salm et al., 2009). Chicha is another beverage staple for many Amazonian populations, including Tsimane', for social reasons, but these drinks also serve as a thirst-quenching source of water (Zycherman, 2013). Chicha can be made with sweet and bitter varietals of cassava, maize, or plantains that is masticated and spit into a pot and combined with water, then set aside to ferment before being consumed (Huanca, 1999). In Harner's (1984) ethnography about the hunter-gatherer Shuar-Jivaro, he states that on average, men roughly consumed 3-4 gallons (11.4 – 15.1 L) of chicha daily, women 1-2 gallons (3.8 – 7.6 L), and children (9-10 years old) half a gallon (1.9 L). According to Harner (1984), raw water was consumed only as a last resort when they ran out of chicha. In a review of chicha use in Ecuador, Cox and colleagues (1987) found that fermented chicha, which generally has a low alcohol content, showed no signs of fecal coliforms and indicated that the fermentation process can potentially make contaminated water potable.

Variation in hydration strategies has implications for many aspects of nutrition and health, including pathogen exposure (Nichter, 1988; Popkin et al., 2010). Unclean water increases the risk of a host of water-borne (ingesting unclean water), water-related (vector-related), and water-washed (lack of hygiene) diseases (Prost, 1993). Gastrointestinal (GI) illness is the most common health outcome of a scarcity of clean water. It results from exposure of a susceptible host to a pathogenic organism through direct or indirect contact with feces (Black & Lanata, 2007). GI illness morbidity in adults results in weight loss, malabsorption, dehydration, loss of economic productivity, and potentially death (Hunter et al., 2009; Mendez & Adair, 1998; Pelto & Pelto, 1989).

The nutrition literature suggests that water intake can be generally broken into a 70/30 split with 70% of water on average coming from liquid sources and 30% coming from food sources (Jequier & Constant, 2010). Chapter 3 of my dissertation examines the generalizability of this statement by asking does this pattern show up in non-industrialized populations without access to clean water and food? Or is this a shift seen in populations once their diets have become industrialized? Do differences in the proportion of water coming from liquid versus food sources affect the risk of GI illness between individuals? Framing the issue of how humans meet their water needs using a human adaptability approach provides an insight into how humans buffer multiple stressors (dehydration, disease) but may also introduce stressors (pathogens) (Haas & Harrison, 1977).

Physiology of hydration and human heat adaptation

To understand the processes of hydration, thirst, and water intake, I review the physiology of hydration and then focus on human heat adaptation as it relates to hydration.

Hydration status is the internal state of water balance within an organism that is constantly in flux (Armstrong, 2007). Regulation of water or fluid balance is largely involuntary, driven by integrative centers in the brain (Popkin et al., 2010). These centers coordinate detectors throughout the body and send messages to the executive organs, kidney, sweat glands, and salivary glands. Water deficits create ionic concentration in the extracellular compartment, which cause cells to shrink as the water moves out of the intracellular space. Popkin, D'ancy, and Rosenberg (2010:441) describe the process:

> This shrinkage is detected by two types of brain sensors, one controlling drinking and the other controlling excretion of urine by sending a message to the kidneys, mainly via the antidiuretic hormone vasopressin to produce a smaller volume of more concentrated

urine. When the body contains an excess of water, the reverse processes occur: the lower ionic concentration of body fluids allows more water to reach the intracellular compartment. The cells imbibe, drinking is inhibited, and the kidneys excrete more water.

The kidneys play a critical role in regulating fluid balance, yet can face extra stress during water scarcity especially when an individual consumes a high salt-diet or if toxins need to be flushed from the system because the kidneys have to produce more concentrated urine (Popkin et al., 2010). Consequently, drinking large amounts of water protects the kidneys. Interestingly, the human body turns over 5-10% of total body water daily (Sawka et al., 2005).

These sensitive homeostatic mechanisms respond to the state of fluid balance within the body and become activated when a deficit or excess of fluid is present beyond 3-400 milliliters of water (Popkin et al., 2010). These water needs are first met by changes in plasma vasopressin concentration and urine flow, whereas thirst and water intake occur if a greater fluid deficit occurs (Valtin, 2002). However, variability has been reported between individuals regarding when thirst sets in, normally between 0.8-2% total body water loss (Popkin et al., 2010). Two subpopulations are at greatest risk of dehydration, children and adults over 70 years of age (Popkin et al., 2010). Children are at heightened risk of dehydration due to the fact that their bodies are comprised of a higher percent water than adults, they have more surface area, and they are not as in tune to thirst as adults (Popkin et al., 2010). Older individuals do not drink as much when they lose water because of defects in osmoreceptors and baroreceptors. As individuals age, thirst and drinking become slightly less tightly woven. Body hydration status may also be linked to apoptotic activity or programmed cell death, though little support currently exists for this hypothesis (Jun et al., 2008).

Recently, Oka and colleagues (2015) published an article in *Nature* which identified two distinct, genetically separable populations of neurons in the subfornical organ that trigger or suppress thirst. Through manipulation of expression of these two populations of neurons, drinking behavior was evoked or suppressed even in water satiated or water thirsty animals, respectively. Their findings suggest that an innate circuit in the mammalian brain acts as a control center for drinking behavior. This finding is significant because it illustrates the evolved response in mammals for brain centers to monitor hydration status and subconsciously seek out or stop drinking behaviors. Maintaining water balance has been shown to be an important part of reducing risk of many chronic diseases including urolithiasis (kidney stones), exercise induced asthma, diabetic hyperglycemia, and hypertonic dehydration in infants (Popkin et al., 2010).

Physical anthropology has a long history of examining adaptations to the thermal environment, which has been proposed as an important selective factor during the evolution of *Homo* through a myriad of traits including body shape, distribution and types of sweat glands, body hair, and skin color (Hanna and Brown, 1983; Wheeler, 1993; Jablonski, 2004; Noakes, 2010; Wells, 2012). The hot-humid microenvironment, present in much of the tropics, raises a key dilemma in the human physiological response to heat, namely the reduced effectiveness of sweat evaporation to cool the body (Hanna and Brown, 1983), thereby increasing stress on the homeostatic hydration process.

Adaptation to the thermal environment has been proposed as an important selective factor during the evolution of *Homo* (Wheeler, 1993; Taylor, 2006; Noakes, 2010; Wells, 2012). Wheeler (1993) contends that the taller, more linear body form of early *Homo erectus* provided it with a selective advantage that reduced relative water needs versus the more compact and robust body of *Austrolapithecus*. This increased efficiency in water storage was due to the taller body of the genus *Homo* that resulted in reduced solar radiation, a shift of the core upward to utilize more ground wind flow, and a higher surface area to core ratio that increased evaporative cooling of the body and thereby reduced water needs. In line with this evidence, two ecogeographical rules, commonly known as Bergmann and Allen's rules, propose that closer to the equator, bodies have smaller cores with longer extremities while in colder climates away from the equator they have larger cores with shorter limbs as a result of thermoregulatory adaptations to different climates (Ruff, 1994; Katzmarzyk and Leonard, 1998; Steegman, 2007; Wells, 2012). While Katzmarzyk and Leonard (1998) found a slightly lower correlation between body proportion and latitude than Ruff (1994), these body shapes play a central role in thermoregulation (Steegman, 2007). Extending this line of thought, body sizes and composition would contribute to water needs and hydration status of modern populations. One would expect to find that individuals with larger body sizes would have greater water needs, which would be amplified in hot environments. Therefore, maintaining fluid balance with larger body sizes would be more challenging and individuals would be more vulnerable to dehydration.

Yet, research also suggests that human heat characteristics are the product of phenotypic modification, or changing characteristics through interaction with the environment (Lee et al., 2004; Taylor, 2006). In fact, it is possible to lose many of the characteristics associated with heat-acclimatization after prolonged time away from the hot-humid environment. Lee et al. (2004) described this phenomenon, known as heat-deacclimatization, by showing that duration of stay in Japan by native Malaysians was associated with shorter onset time of sweating and higher sweat volume at lower temperatures when compared to native Malays. This research illustrates that human heat adaptation is a flexible process as the phenotype interacts with the environment. Therefore, it is possible that the homeostatic process of hydration is subject to environmental phenotypic modification.

The main physiological adaptation to humid heat is the combination of cutaneous vasodilation and a ready onset of sweating (Taylor, 2006). In a review of genotypic versus phenotypic heat adaptation, Taylor (2006) generalized that native populations in hot-humid environments had lower skin blood flow and higher skin temperature leading to more efficient evaporation of sweat and reduced sodium loss compared to non-indigenous populations. Hanna and Baker (1974) noted that Shipibo Indians had lower increases of heart rates with rising temperature yet actually sweated more at moderate levels of activity in comparison with a heat acclimatized mestizo population in the hot-humid Peruvian Amazon. However, many of the early adaptability studies did not measure hydration status alongside these other variables of heat tolerance (Frisancho, 1993). These differences in heat tolerance may confer advantages that would be translated to better hydration in high temperatures.

Many adjustments to humid heat are behavioral and cultural rather than physiological or genetic, which have implications for hydration status (Hanna & Baker, 1974; Ladell, 1964; Frisancho, 1993). Settlements are often built near a water source to utilize wind flow. Minimal clothing allows for maximum skin surface available for sweat evaporation and either open or closed housing is used to cool or warm insides. Behavior follows a pattern to reduce exposure to heat with work beginning in the early morning, midday rest followed by moderate work (Hanna & Baker, 1974; Moran, 2008).

Yet, these work patterns still often result in voluntary dehydration (Ulijaszek, 2001). The phenomenon of voluntary dehydration has long been observed in humans, where workers and athletes do not consume enough water to replenish lost fluids during work or exercise (Hanna and Brown, 1983; Ulijaszek, 2001). Noakes (2010) contends that voluntary dehydration and uncoupling thirst from hydration status is evidence of an evolved human response to water scarcity. Citing the Ju/'hoansi San's endurance or persistence hunting technique, Noakes (2010) states that humans are able to deal well with dehydration without severe consequences and rehydrate later. If humans were not able to voluntarily dehydrate, meaning that they immediately felt the symptoms of dehydration even at low levels of dehydration, then productivity would decline because they would constantly be seeking rehydrating beverages and foods. It is possible that the hot-humid environment is another environmental selective pressure that facilitated the development of voluntary dehydration.

Hydration status is a major component of human responses to heat that has not received adequate attention outside of laboratory or athletic studies examining performance (Armstrong et al., 1997; Casa et al., 2010; Garrett et al., 2014). Ulijaszek (2001) discussed how extreme environmental conditions may lead to voluntary dehydration. Using water loss models through sweat during four and five hour work days among Australian Aborigenes, Ulijaszek (2001) showed that work scheduling is paramount during their summer as water losses in different ecological zones lead to significant dehydration. If activity scheduling is not implemented, dehydration can be so severe as to cause death.

The literature and theory for human adaptation to climate and human adaptability indicates that water and temperature have been key selective pressures during the evolution of *Homo* that have resulted in a relatively fine-tuned homeostatic process of hydration. However, several key questions remain unanswered from this literature. First, do temperature fluctuations directly drive hydration status rhythms among native populations living in a hot, humid environment? Second, how do lifestyle changes relate to hydration status? And finally, is it possible to remain well-hydrated while undergoing physical exercise in challenging conditions or is there evidence for voluntarily dehydration throughout the day? Chapter 4 addresses these questions by using ethnographic observation techniques through focal follows, ambient temperature measurements, urinalysis, and anthropometrics.

Water insecurity

How humans respond to environmental constraints is a key factor in understanding human adaptability. As Huss-Ashmore (2000:9) aptly states, "Any living organism has two basic adaptive tasks: to avoid stressors and to procure critical resources in sufficient quantities for survival and reproduction." In this vein, water is the most critical resource necessary for survival for all human and non-human primates. Humans can only survive up to seven days without access to water and can only lose up to 10-15% of their total body water before risk of death (Kleiner, 1999). Wutich and Brewis (2014) contend that water is a greater stressor than food. Utilizing the ethnographic record, they found evidence that multiple populations chose to increase their access to water at the expense of food access. Perception of water sources and the water environment then may have played equally critical roles in affecting human behaviors and decisions regarding where to live in relation to water resources similar to food resources, especially during times of environmental stress, like water scarcity, heat waves, or flooding conditions.

Currently, many populations face water scarcity as a result of limited freshwater supplies, overuse, or inadequate distribution systems (Gleick, 2009). Water security is defined as "sufficient access by all people, at all times, to adequate water for an active and healthy lifestyle" (Wutich and Ragsdale, 2008). Water insecurity is then defined as "insufficient and uncertain access to adequate water for an active and healthy lifestyle" and has three key dimensions:

inadequate water supply, insufficient access to water distribution systems, and not providing enough water for a healthy lifestyle (Stevenson et al., 2012). Water insecurity falls under a broader anthropological concern with resource scarcity (Wutich & Brewis, 2014), but has gained momentum in the scientific literature since 2000 (Cook and Bakker, 2012). Recently anthropologists have explored the domain of water insecurity among populations facing water issues in places as diverse as Alaska, Bolivia, Ethiopia, and Mexico (Eichelberger, 2010; Ennis-McMillan, 2001; Stevenson et al. 2012; Wutich and Ragsdale, 2008; Wutich & Brewis, 2014).

Inadequate water supply can result from structural and gender inequalities, where larger economic policies prevent certain populations, like women or poorer populations, from equal access to water (Ahlers, 2005; Bustamante et al., 2005). Many anthropologists have critiqued neoliberal economic policy for its inequitable distribution of water rights as it has led to the wealthy getting richer and limiting access to the poor (Davila-Poblete & Rico, 2005; Whiteford, 2005; Zwarteveen & Bennett, 2005). These policies often view water as a commodity or economic good, which skews the symbolic and cultural value populations assign to water (Delgado, 2005; Orlove and Caton, 2010).

Many solutions have been proposed to deal with water scarcity ranging from technological to economic, such as tiered pricing or cost-recovery measures (Alfaro, 2005; OECD, 1999). Other researchers have proposed an entitlements approach to water distribution and pricing citing institutional failure as the cause of water scarcity, drawing a comparisons to Sen's (1981) view on food distribution (Anand, 2007). According to Gleick (1996), to meet basic human needs an individual needs 50 liters of water daily. These basic needs include water for drinking, cooking, and sanitation. Recently, researchers have investigated how individuals and populations cope with water insecurity, examining their cultural and social strategies (Arar, 1998; Wutich, 2009; Wutich, 2011). Borrowing water, and reciprocal water exchanges are important strategies in areas with low water security, as social networks can act as a form of social insurance to buffer hard times (Wutich, 2011). Water insecurity can result in emotional health problems as several researchers have described cultural idioms of distress as individuals "suffer from water" (Ennis-McMillan 2001; Wutich & Ragsdale, 2008). Depression and anxiety are two common emotional responses in water insecure populations.

Researchers interested in water use at the household and community levels assess local practices, beliefs, perceptions, and knowledge related to water because of health implications. Perception of water quality and water systems affect decision-making regarding the source used as individuals are more likely to use water sources they perceive to be clean (Nagata et al. 2011). Perception is in many ways informed by water knowledge, which has recently been explored as a form of local ecological knowledge (Gartin et al. 2011). Hanna and Brown (1983) hypothesized that early humans would have used mental maps to know where important water resources were in its environment.

Perceptions of water sources are also affected by health education campaigns (De Ver Dye et al., 2011). Health interventions, such as boiling water for treatment or providing oral rehydration salts, have targeted local beliefs and practices because of their ties to diarrheal diseases (Burghart 1996; Nichter 1988; Wellin 1955). Many of these interventions have been ineffective because they fail to first understand the local cultural and medical systems present (McLennan 2000; Nichter 1988). Individuals interpret health messages through a cultural lens and ascribe their own meaning onto them (Nichter 1985; Nichter 1988). Whether water quality is more important than water quantity has been another important issue in this literature as evidence has shown that water quality only improves health if there is a sufficient amount (Arar 1998; van der Hoek et al 2001; van der Hoek et al 2002).

It is clear that individuals who live in water scarce conditions, in deserts and regions prone to aridity and drought without adequate water supplies can experience water insecurity, but do individuals living in water-rich environments where the available water is unclean through fecal contamination also experience the same types of worry and suffering from water? Moreover, do those experience-based measures of water insecurity relate to prevalence of diarrhea and dehydration for themselves and their children? Finally, while flooding clearly affects water quality and disease patterns, do individuals responding to a flood deal with it in a manner analogous to drought? Chapter 5 attempts to answer these questions through a combination of semi-structured interview, survey, and biological methods.

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CHAPTER 3

WATER FROM FRUIT OR THE RIVER? EXAMINING HYDRATION STRATEGIES AND GASTROINTESTINAL ILLNESS AMONG TSIMANE' ADULTS IN THE BOLIVIAN AMAZON[1]

[1] Rosinger, A., & Tanner, S. 2015. Water from fruit or the river? Examining hydration strategies and gastrointestinal illness among Tsimane' adults in the Bolivian Amazon. *Public Health Nutrition,* 16(6): 1098-1108. Reprinted here with permission of the publisher.

Abstract

Objective: Water is an essential nutrient overlooked in many cross-cultural studies of human nutrition. This article describes dietary water intake patterns among forager-horticulturalist adults in lowland Bolivia, compares daily intake to international references, and examines if variation in how people acquire water relates to gastrointestinal illness.

Design: Cross-sectional observational study used survey, anthropometric, and qualitative methods with Tsimane' adults selected by age and sex stratification sampling in one community.

Setting: Research occurred in one Tsimane' village in the Beni department, Bolivia with limited access to clean water. 24 h diet- and health-recalls were conducted in July-August 2012 and qualitative interviews/ethnographic observation in September-October 2013.

Subjects: Forty-five Tsimane' household heads (49% men) took part in the first data collection and twenty-two Tsimane' (55% men) were included in the follow-up interviews.

Results: Men and women reported consuming 4.9 litres and 4.4 litres of water from all dietary sources, respectively. On average, water from foods represented 50% of total water intake. 13% of participants reported symptoms of gastrointestinal illness. In a logistic regression model adjusted for age, BMI, sex, and raw water consumed, each percent increase in water obtained from foods was associated with a reduced risk of GI illness (OR = 0.92, 95% CI 0.85, 0.99).

Conclusions: Both total water intake and percent water from foods were higher than averages in industrialized countries. These findings suggest people without access to clean water may rely-on water-rich foods as dietary adaptations to reduce pathogen exposures.

Introduction

Access to improved water sources, such as hand pumps or other technology designed to protect against fecal contamination, continues to be a critical public health problem among rural indigenous populations in low-income countries (WHO & UNICEF, 2014). To complement this need, this study examines how individuals use local environmental resources to acquire water and the resulting health consequences (Vargas). Dietary flexibility serves as an adaptation to environmental constraints and relates to variation in nutrition, health, and disease patterns (Pelto et al., 2000; Stinson, 1992). Humans have long used behaviors and food processing techniques as culturally-integrated buffers that reduce toxicity and increase the digestibility and nutrients of food, such as the 10-day processing of bitter manioc (Dufour, 1995), corn alkali processing to reduce niacin deficiency (Katz, 1987), and fire and cooking (Ungar et al., 2006). Likewise, researchers hypothesize that humans have historically used dietary strategies to flexibly meet their water needs, such as eating fruits when water is unavailable or using beer, gruel, or cider fermentation to render dirty water drinkable and potentially medicinal (McClatchey & Reedy, 2010; Nelson et al., 2010). In this paper we describe hydration strategies, or a person's daily water intake derived through a spectrum of foods and liquids, among a sample of adult Tsimane' forager-horticulturalists living in the Bolivian Amazon. We then examine the relationship between different hydration strategies and reported symptoms of gastrointestinal illness. This paper focuses on Tsimane' because they lack access to clean water, yet are highly active and live in a hot, humid environment, creating high water needs. Additionally, previous research has documented high prevalence of water-related diarrheal diseases and parasitic infection (Blackwell et al., 2011; Tanner et al., 2013).

Water recommendations and cross-cultural strategies

Water is an essential nutrient comprising 40 to 65% of total body weight. Because human water needs exceed the body's ability to produce it (Jequier & Constant, 2010), obtaining enough water on a daily basis is critical to physiological and cognitive health (Murray, 2007). Therefore, in addition to the metabolic process of oxidation (~250 ml/per day) (Vivanti, 2012), humans consume water from various sources including liquids (plain and raw water and other beverages) and foods. In this paper "raw water" refers to natural, untreated water, "plain water" refers to treated, drinking water, and "water" refers to physiologically available water within foods or liquids.

Daily water intake recommendations are based on several sources. The U.S. Institute of Medicine (IOM) has set adequate intake levels (AIs), or experimentally-derived values expected to meet the nutritional adequacy for moderately active individuals in a healthy population, of 3.7 liters for men and 2.7 liters for women daily (IOM, 2004). The European Safety Food Authority (ESFA) recommends lower water intake at 2.5 liters and 2.0 liters for men and women (EFSA, 2010). Both of these recommendations rely on average intakes from national nutritional studies as well as water turnover studies and note that recommended intake levels vary with body size, activity levels, metabolism, clothing, temperature, illness, and pregnant and lactating status (Sawka et al., 2005). For a detailed commentary of the evidence behind the IOM's AIs, see Sawka et al. (2005). These recommendations have been critiqued for not distinguishing between sources of hydration (e.g., between water from sugar-sweetened beverages and plain water, tea, and coffee) and not emphasizing the water potential of foods (Popkin et al., 2006; Tsindos, 2012). Recently, research has called for studies to document water intake in cross-cultural settings to substantiate AI recommendations (Armstrong, 2012).

Comparative research demonstrates slight differences in total water intake across countries as well as worldwide differences in hydration strategies depending on local ecology and food culture (de Garine & de Garine, 2001; Nagata et al., 2011; Paque, 1976). Using the U.S. National Health and Nutrition Examination Surveys (NHANES), Kant, Graubard, and Atchison (2009) found adult men consumed an average of 3.5 liters and women 2.9 liters of water daily. Interestingly, the majority of water was consumed in liquid form (33% plain water and 48% purchased beverages) and only 18% from foods. A 1995 Australian national nutritional survey found similar total water intake values (men 3.4 liters, women 2.8 liters), but slightly more water (~25%) was derived from food sources (McLennan & Podger, 1998). In Germany, a recent nutritional survey demonstrates lower average total water intake values (men 2.5 liters, women 2.1 liters) but that food sources were a more important source of water (~29% of water intake) (Manz et al., 2012). Finally, in Highland Ecuador, Berti and Leonard (1998) found comparable daily water intake levels (men 2.6 liters, women 2.4 liters), but a still greater proportion of water coming from food sources (~35% from tubers, grains, and fruits/vegetables, ~65% from water and milk). Overall, existing nutrition surveys demonstrate that water intake levels are within ranges recommended by the IOM and ESFA but that variation exists in hydration strategies, with a range of ~81% of water coming from liquids in the U.S. to ~65% in Highland Ecuador.

Across Amazonia, fruits, tubers, and traditional fermented beverages are important components of hydration strategies likely because of limited access to clean water (Clement 2006; Nelson et al., 2010). For example, the açaí palm's drupes (*Euterpe oleracea*) and coconuts are important sources of energy and hydration for Kayapo and Ribeirinhos of Brazil (Salm et al., 2009; Piperata et al., 2011). Chicha (a home-made fermented beer) is a beverage staple for many Amazonian populations, including Tsimane'. While chicha is important for social reasons, functionally it quenches thirst and hunger (Zycherman, 2013). Chicha can be made with sweet or bitter varietals of manioc, maize, and plantains, is masticated, combined with water, and set aside to ferment before consumed (Huanca, 1999). In an ethnography about the hunter-gatherer Shuar-Jivaro, Harner (1984) states that on average, men consumed ~3-4 gallons (11.4 – 15.1 liters) of chicha daily, women 1-2 gallons (3.8 – 7.6 liters), and children (9-10 years old) half a gallon (1.9 liters). According to Harner (1984), raw water was consumed only when chicha was unavailable.

Differences in hydration strategies, e.g., consuming water from raw sources instead of foods or market beverages, have direct implications for nutrition and pathogen exposure (Nichter, 1988; Popkin et al., 2010). Currently 748 million people worldwide, including Tsimane', lack access to clean water, which increases the risk of water-borne gastrointestinal (GI) illness (WHO & UNICEF, 2014). GI illness is the most common health outcome of a scarcity of clean water and results from exposure to a pathogenic organism through direct or indirect contact with feces (Black & Lanata, 2007). GI illness morbidity, while more dangerous among children, is associated with weight loss, malabsorption, dehydration, loss of economic productivity, and potentially death among adults (Hunter et al., 2009; Mendez & Adiar, 1999; Pelto & Pelto, 1989).

This paper has two goals: 1) to describe water intake and compare differences in hydration strategies among a population without regular access to clean water to international recommendations, and 2) to examine how variation in hydration strategies is associated with GI illness.

Background and methods

Study Population and Fieldsite

This research was conducted among Tsimane', a forager-horticulturalist indigenous population living in the department of Beni, in northeastern Bolivia (Zycherman, 2013). Traditionally semi-nomadic, Tsimane' now live in permanent villages that resulted from renewed missionary efforts in the 1950s (Reyes-Garcia, 2001). These permanent villages have been an impetus for increased engagement with the Bolivian government, regional market economy, and outside organizations. Recent estimates show that their population has almost doubled in the last 25 years to ~15,000 in ~100 villages. While Tsimane' maintain many aspects of their traditional lifestyles, market participation has increased rapidly leading to increased access to market foods and beverages, thus precipitating dietary changes (Ringhofer, 2010; Rosinger et al., 2013). The typical Tsimane' diet consists of self-produced and gathered/hunted foods, such as manioc, plantains, maize, rice, fruits, chicha, fish, chickens, game meat, and some market foods, such as dried and salted meats, sugar, pasta, lard, vegetable oil, and white flour/bread (Byron, 2003). Food sharing within households and common pot cooking and eating is normal. Various fruits are eaten seasonally, but Ringhofer (2010) contends they add diversity to the diet rather than serving as a primary calorie source.

The Lowlands of Bolivia, like most of Amazonia, are characterized by a scarcity of clean water (Rufener et al., 2010). Across Tsimane' villages, six raw water sources exist: river, streams, ponds, open and covered wells, and collecting rainwater. In October 2013, the first author (A.R.) conducted water quality analysis in the study community from the river (two samples), open well (one sample), and covered pump well (one sample) in collaboration with the environmental health laboratory of SEDES Beni, in Trinidad, Bolivia. The analysis revealed presence of *Escherichia (E.) coli* and fecal coliforms in the water samples from the river, presence of fecal and total coliforms in the sampled open well, while non-pathogenic total coliforms were found in the sampled closed pump well (Unpublished results).

Much of the health-related research among Tsimane' reveals that the majority of diseases are infectious. Tsimane' children and adults have a 56-80% prevalence of parasitic helminthic infections (Blackwell et al., 2011; Tanner et al., 2013). Infectious diseases, including GI infection, historically have accounted for more than 50% of all deaths (Gurven et al., 2007). Additionally, many Tsimane' consume water from untreated surface sources and water quality is likely worse than in the past due to increased population density, runoff from agricultural and livestock, use of toxic detergents, and use of motorcycles and cars (Gurven et al., 2007). Nevertheless, it is unclear how much water Tsimane' consume and how hydration strategies are associated with GI illness among this population.

Study Design

During July-August 2012, the first author conducted a cross-sectional observational study using 24 h multiple-pass dietary recall interviews, a demographic survey, and anthropometric measurements with 45 adults in one Tsimane' community. Our sampling strategy used sex, age, and geographic stratification from a community census listing all households. Once stratified, participants in five geographic zones were asked to participate. The goal was to obtain a roughly representative sample of the 105 (51 males) household heads in the community (See Table 1 for sample characteristics). Geographic zones were important to assess because extended families cluster in a zone and share similar water sources. Twenty-five of the fifty-five households in the community are represented in this sample with one or both household heads interviewed. This research was conducted during the dry season when rainfall was infrequent. In the study community, people had access to the Maniqui River, a stream, seven open wells (hereafter, wells), and eight covered cement wells with hand-pumps (hereafter, hand-pumps). During September-October 2013, the first author returned to the study community and conducted follow-up semi-structured interviews with 22 household heads (12 male, 10 female). Here, four to five households in each geographic community section were selected based on age, sex, and relationship to neighbors. Twelve household heads were interviewed during both segments of the study. Interviews were conducted in the participants homes and lasted, on average, one hour, and were audio-recorded. Topics included diet, thirst, dehydration, water sources, water quality, and diarrhea treatments.

The Institutional Review Board at the University of Georgia approved the study protocol (IRB #2012-10290-0). Permission to work in the community was received from the Grand Tsimane' Council and community members. Verbal consent was obtained from each individual prior to data collection and witnessed by family members. A native Tsimane' speaker worked as a translator and assistant for this research.

Multiple-Pass Diet Recall

To collect information on individual food and liquid intake, we used 24 h multiple-pass diet recall following procedures by Lee and Nieman (2007a). This method has been validated for dietary intake (Conway et al., 2004), is less invasive and time consuming than the weighed food record method, and does not alter the usual diet (Lee & Nieman, 2007a). A 24 h activity recall was also conducted prior to the dietary intake survey and activities from the previous day were used to prompt recall about foods and drinks consumed before, during, and after meals.

The estimation of quantity and volume of foods and liquids consumed was aided by the use of locally-used plates, mugs, and tutumas (a local bowl made from the shell of *Crescentia* *cujete)*. For fruits that varied in size, such as papayas and plantains, individuals indicated if the fruit was small, medium, or large to best estimate the weight. The majority of meals are prepared in a common pot (e.g., soups, rice, fish, or other mixtures). For these foods, homogeneity of items in the pot was assumed per individual following Berti et al. (2010). Multiple passes were made on each food interval (breakfast, between breakfast and lunch, lunch, etc.), meaning that when the respondent stated they did not eat or drink any other item, the interviewer reviewed the items and amounts consumed with the respondent and others present, which allowed the respondent to revise estimates or make additions or subtractions before moving on to the next interval (Lee & Nieman, 2007a). This sequence was repeated until the end of the 24 h period. The interviewer also used discarded food items around the house to prompt recall.

Independent Variable: *Water Intake*

Water intake was calculated manually from the weight or volume of each item listed in the diet recall into ml of water using the Bolivian Food Composition Tables (Minesterio de Salud y Deportes, 2005) and the USDA National Nutrient Database for Standard Reference (2011). While the Bolivian food tables contained the majority of foods reported, the USDA database contains water contents for cooked foods and has been used for other nutritional studies in rural Bolivia (Lazarte et al., 2012). We consulted the Food and Agriculture Organization (1994) to estimate water content of sugarcane because it was not listed in either database. We divided water sources into five main categories (See Table 2): 1) water from foods; 2) raw water, or water from the river, stream, wells, or pumps; 3) raw water mixed with other items, like powdered flavoring, sugar, or squeezed fruits; 4) water from chicha; and 5) water from market beverages (i.e., store bought drinks, such as sodas). Next, to assess each individual's hydration strategy, we divided the amount of each of the five categories by their total daily water intake.

This conversion calculated percent water intake from each category, standardizing for total water intake. This was necessary because total water intake is proportional to body size, activity patterns, and temperature.

Dependent variable: Gastrointestinal illness

After the diet recall, individuals were asked a series of questions regarding current health status, including illnesses and symptoms (diarrheal, respiratory, or other sickness) they were experiencing at the time of the interview (see Table 3). Individuals were considered to be suffering from GI illness if they reported one or more of the following symptoms: stomachache, diarrhea (three instances of watery stool in the past 24 hours), or vomiting. Recall of illness is commonly used to assess health conditions (Shelling et al., 2005), yet recall periods that extend beyond three days begin to underestimate true disease prevalence (Feikin et al., 2010). We focus our analysis on GI illness because this is the most salient health outcome of water intake.

Covariates

We controlled for a number of factors, including age, sex, and body composition, that contribute to water needs and are reflected in water recommendations. Age was measured by asking individuals their birthdate, how old they were, and verified with a birth certificate when possible. Body composition was assessed through anthropometrics. Weight was measured using a Tanita bioimpedance scale (accuracy 0.1 kg) and height using a standing stadiometer rounded to the nearest 0.1 cm (Lee & Nieman, 2007b). BMI was calculated from weight and height as kg/m^2 (Shaw & Braverman, 2012). All measurements were taken three times with the average used in the analysis.

Water Quality Analysis

Water samples were collected and transported following methods laid out by the United States Geological Survey (2006) [57] from 4 sites in the community: the river (two samples), open well (one sample), and covered pump well (one sample). Three indicators of water quality were measured: turbidity, fecal coliforms, and E. coli. Turbidity was measured using a calibrated nephelometer. 100 ml of the water samples were added to Hach presence/absence broth containers (Hach Company, 2013) to measure fecal coliforms and E. coli. At the laboratory, the Hach containers were placed in an incubator at 35 degrees centigrade. Following 24 hours of incubation, the water samples were checked for conversion of color and fluorescence, which indicates presence of fecal coliforms and E. coli, respectively.

Statistical Analysis

Data was entered into Microsoft Excel, and each dietary item was converted to water content using the food composition tables and databases described above. Data was then transferred to the Stata statistical software package version 13 (2013; StataCorp, College Station, TX, USA) for analysis. Alpha (α) was set to 0.05 using two-tailed tests, robust standard errors, and 95% confidence intervals. The outcome variable (reported GI illness) is dichotomous, so we used the student's t-test to examine differences in hydration strategies between individuals who did and did not report GI illness. Next, logistic regression analysis was used with robust standard errors clustered by household to address potential confounding of household membership, dietary intake, and transmission of GI illness within the household. Finally, using the margins command in Stata, we assessed the predicted probability of GI illness using coefficients and sample means from the logistic regression. Predicted probabilities calculated from logistic regression are often preferable to odds ratios, because they do not overstate associations with rare outcomes and lend themselves to visual representations of results (Graubard & Korn, 1999).

Results

Hydration Strategies

Men and women in the sample reported an average of 4.95 liters and 4.43 liters of water daily, respectively (see Table 1). Hydration strategies between men and women were similar with men and women acquiring approximately 48% and 50% of water from food sources, 18% and 22% from raw water, 20% and 13% from chicha, 12% and 11% from mixed raw water; and 3% from market bought beverages, respectively. Four percent of individuals obtained water from all five categories of water, 40% used four of the five categories, and 38% used three of the five categories. Food was consumed by all participants and contributed between 0.18 and 5.15 liters of water (see Table 2).

Nearly the entire sample (96%) drank some raw water (range of 0 to 2.42 liters), with the majority using the river or hand-pumps as their primary raw water source. The predominant cultural construct of clean raw water in this sample related to clarity. During the follow-up interviews, all 22 of the participants mentioned clarity and turbidity as the primary indicators of how they judge cleanliness when asked “what makes water clean/dirty?” Moreover, the majority of interviewees stated that they let the water settle before consuming it, but used no other treatment methods with the exception of one individual who reported boiling water in the past few months. While most participants indicated they believed the hand-pumps and wells were a cleaner source of water than the river because the water was clearer, distance to the water source was also a major factor in their decision-making process. These perceptions of water cleanliness were consistent with water quality analyses conducted in 2013 by the first author as the hand-pumps were negative for fecal coliforms and *E. coli* and had a turbidity of 10 Nephelometric Turbidity Units (NTU). The well water was slightly clearer with a lower turbidity reading (5 NTU) but was positive for fecal coliforms. Ground water sources generally have turbidity around 5 but can range up to 19 NTU (USGS, 2006). The river's average turbidity reading was much higher at 57 NTU and was positive for *E. coli* and pathogenic fecal coliforms. Overall, participants rated the river as the dirtiest raw source and the hand-pumps as the cleanest.

Water came from many sources and 62% of individuals reported mixing raw water (0-2.7 liters) with either sugar, a purchased vitamin-c fortified powdered flavoring, or juice extracted from fruits, sugarcane, and chive (ground manioc). During follow-up interviews, interviewees stated they preferred these "refrescos" because they were easier to drink and encouraged hydration. During participant observation, the consumption of sugar mixed with raw water was commonly observed, and parents frequently gave this mixed beverage to young children. While mixing these items with raw water may make beverages more palatable, it does not clean the water. Slightly over half of the sample (56%) reported drinking chicha (0 to 3.9 liters), with men consuming more than women. Finally, 18% of the sample reported drinking market beverages, such as sodas, beer, and chocolate milk (0 to 1.47 liters).

Hydration Strategies and GI Illness

Cases of GI illness were strongly related to primary water source. Of the 13% of adults reporting GI-related symptoms, all of the cases came from people who used the river (2 of 22) and stream (4 of 6) as their primary water sources. No cases of GI illness were reported among those who used wells or hand-pumps. These results are consistent with the water quality analysis described above indicating the river had more contamination than other sources.

Individuals with GI illness did not have statistically different total water intake than those without GI illness (5.0 liters vs 4.6 liters, p=0.42). When we examined the hydration strategies of individuals who reported GI illness versus those who did not, we found differences in the percent of water coming from foods versus liquids. First, those with GI illness consumed 35% (1.8 liters) of their water from food and those without GI illness acquired 52% (2.4 liters) of their water from food (t=2.55; p=0.015). Additionally, market beverages (soda, specifically) accounted for 8% (0.4 liters) of water intake for those with GI illness and only 2% (0.1 liters) for those not experiencing symptoms (t=-2.08; p=0.044). Individuals who reported GI illness did not obtain significantly different percentages of their hydration strategy from raw water sources and chicha than those without symptoms (p=0.44; p=0.36, respectively). Finally, mixed raw water intake was similar among those with and those without GI illness (9% versus 11%, p=0.71).

Regression analysis

Using logistic regression, we estimated the odds of reported GI illness by percent water acquired from food sources. Each percent increase in *water obtained from foods* was associated with 6% lower odds (p=0.032) of GI illness (see Table 4, model 1). Restricting the logistic regression to individuals who obtained their water from the river or stream (n=28) did not change the strength of the association but did reduce the statistical significance slightly due to reduced power (OR=0.94; 95% CI: 0.88, 1.00; full results not shown). After controlling for gender, age, and BMI, the relationship between water intake from food and GI illness remained significant (model 2, OR=0.91; p=0.050), the strength of the association increased, and the fit of the model to the outcome data improved (pseudo r^2 increases from 0.15 to 0.25). Further, we assessed the association of the absolute volume of raw water consumed (per 100 ml) on the probability of GI illness. Model 3 indicated that the association between raw water consumption and GI illness is significantly related after controlling for covariates. Each 100 ml of raw water consumed was associated with 12% higher odds ($p=0.05$) of GI illness. When controlling for raw water consumed, as well as sex, BMI, and age, percent water from foods remained significantly negatively associated with GI illness (Model 4, OR=0.92; $p=0.019$).

Using the coefficients from model 4, Figure 1 illustrates how the predicted probability of GI illness changed depending on how much water an individual consumed from food sources. According to the statistical model, the probability of GI illness decreased in a non-linear fashion as water intake from food sources increased. In fact, the predicted probability of GI illness was significantly higher than the sample average (13%) among individuals who obtained less than 43% of their water intake from food sources. At the high end of the range of water acquired from food sources reported in the sample (73%), the probability of GI illness was less than 1%.

Discussion

Very little water intake data exists for non-industrialized populations, especially forager-horticulturalist populations, so it is difficult to know how water recommendations match actual population consumption. Tsimane' men and women in this sample consumed an average of 1.2 liters and 1.7 liters more water than the IOM's AI water recommendations (3.7 liters and 2.7 liters). The difference is greater when compared to the ESFA's recommendations (2.5 liters and 2.0 liters). This difference in water intake is most likely due to high ambient environmental temperatures, coupled with moderately high physical activity levels (Gurven et al., 2013). However, despite the higher absolute reports of water intake, it is difficult to judge whether these levels are sufficient to meet water needs, particularly during the dry season when Tsimane' engage in physically demanding labor clearing fields for planting. During follow-up interviews, all informants reported experiencing thirst (*jari'rij*) and dehydration (*chanij*) daily and that these symptoms were most severe when working in their fields.

Nevertheless, individuals in this sample reported a high diversity of dietary items in their hydration strategies. The majority of participants used water from foods and raw water in addition to either chicha, mixed raw water, or market drinks. Most strikingly, Tsimane' in this sample obtained ~2.3 liters of their water from foods or almost 50% of their total water intake, much higher than the 0.7-1.0 liters (or 19-32%) reported among industrialized populations (Kant et al., 2009; Jequier & Constant, 2010). Many of the fruits in the Amazon, such as papayas, grapefruits, and oranges, are water-rich and contain 80 to 90% water (Clement, 2006). Additionally, dietary staples like plantains and manioc, which are consumed with almost every meal, provide significant amounts of water although the content varies by method of food preparation. For example, a plantain is 65% water yet cooking it in water increases water content to 67% and frying it reduces water content to 49% (USDA, 2011). These differences in food preparation can have multidimensional consequences, for not only does frying plantains increase the fat and caloric contents, but it may encourage people to get more water from less clean sources.

In relation to GI illness, river and stream raw water sources, but not wells or hand-pumps, were associated with risk of reporting symptoms in this sample. The hand-pumps had a closed cement cover that prevented contamination from entering the water source as well as soil filtration of the water and were the only source that was not contaminated with pathogenic fecal coliforms or *E. coli*. In this community, none of the water sources have individual ownership and are free for all to use. The hand-pumps were built near several groups of homes and communal locations during public health interventions in the early 2000s (Ringhofer, 2010) and again in early 2012.

Water clarity, which was the main attribute listed when asked to judge water cleanliness, can serve as a proxy for relative cleanliness, i.e. between the river which was highly turbid and the wells or hand-pumps. Clarity cannot be used to discern between the water quality of the well and hand-pump because the hand-pump had higher turbidity than the well, but was negative for contamination. These results are similar to reports from Puerto Rico and Brazil, where turbidity levels were associated with sensory, or organoleptic, perceptions of water quality, and affected the likelihood of treating water by filtration or boiling, and searching for alternative water sources or buying bottled water (Jain et al., 2014; Queiroz et al., 2013). Other studies have found that odor and taste also affect perception of water quality but are often uncorrelated to objective water quality (Orgill et al., 2013). Individuals experiencing GI illness who relied on the river or stream as their primary water sources stated that the only times they switch to a well or a hand-pump was when the water was highly turbid or had a bad odor. These sentiments are interesting to consider for future water-related public health interventions as turbidity levels, placement, and travel time of improved water sources relative to alternative sources may affect behaviors and effectiveness of interventions.

It is clear that while the primary raw water source is important to consider, it does not fully explain GI illness risk as many individuals who used the river water did not report GI illness. Hydration strategies must be studied holistically as we found that increased water from foods, but not other sources, was associated with decreased risk of GI illness. This finding echoes McClatchey and Reedy’s (2010) assertion that apples are a container of clean water. In this sentiment, the Amazon is a fruit-rich environment with the ground acting as a water purifier

(Clement, 2006). For example, papayas grow year-round in Tsimane' horticultural fields (Huanca, 1999). These fruit are a good source of energy when working, but one large papaya with pink flesh (88% water) also contains ~687 ml of clean water (USDA, 2011). Recent research suggests that increasing water from whole foods may improve health and hydration, especially after physical activity (Potter, 2011; Sharp, 2007). Consuming a large amount of water from foods may serve as a nutritional adaptation by reducing exposures to pathogens in an environment without access to clean water.

Similar to other Amazonian populations, chicha is an important part of Tsimane' hydration strategies, yet we did not find any association between it and risk of illness. In a review of chicha use in Ecuador, Cox and colleagues (1987) found that fermented chicha showed no signs of fecal coliforms and indicated that the fermentation process can potentially make contaminated water potable. Likewise, the fermentation process of cider and beer has been cited as a mechanism to purify water (McClatchey & Reedy, 2010; Nelson et al., 2010). A possible explanation for the lack of an association in this study could be due to grouping chicha into one category when different individuals consumed batches of chicha with different levels of fermentation.

Limitations

This study is subject to several limitations. First, the relationships in this paper should be viewed as associations because this is a cross-sectional study. Previous research among Tsimane' has found that the average community has ~20 households and water is commonly drawn from the Maniqui river and streams (Godoy et al., 2010). In comparison, this study community is large (55 households) and has access to several water sources. While a small sample size drawn from one community reduces the generalizability of the results to the larger Tsimane' population, we do not believe that selection bias is present within the sample due to the sampling strategy. Each geographic zone was equally represented to avoid over-representing closely related household clusters and to accurately capture the use of each available water source. When comparing the nutritional characteristics of the adults in this sample to recent research (Rosinger et al., 2013) on an exhaustive sample of Tsimane' adults in 40 randomly chosen communities, women in this sample had higher weights and BMI (61.3 vs 53.8 kg and 23.7 vs 25.8 kg/m^2), but there were no differences in other demographic factors. This difference may affect the absolute amount of water intake of women as larger body sizes require more water and may partially account for why women's reported water intake in this sample are 1.7 liters higher than the IOMs recommendations for women, whereas men's intake are 1.2 liters higher. Higher BMI, which is controlled for in the logistic regression models, should not bias the probability of infection with GI illness.

Additionally, with only one 24 h dietary recall for each individual in the dry season, we cannot measure intra-individual variation, nor can we comment on changes in hydration strategies throughout the year as environmental resources change. However, fifty days of participant observation during both periods of data collection indicated that dietary intakes are relatively consistent as individuals relied on the same dietary staples (plantain, manioc, rice, pasta) daily with changes in the main protein source (fish, dried-salted pork, or hunted game). Additionally, these foods are among 21 dietary items that comprise >90% of caloric intake among this population (Zeng et al., 2013). This suggests that the dietary intakes reported here are good indicators of the general diet in the community during the dry season. The weight/volume of foods and liquids consumed were an estimation made by participants and any estimation errors were transferred to the conversion of water intake (Grandjean, 2012), yet we do not believe that any potential errors would be systematically biased.

The association between water intake from food and GI illness may be subject to reverse causality bias. Individuals may shift their hydration strategies when sick with GI illness leading to the pattern observed in this paper. Many populations are known to restrict intakes of foods or change hydration strategies when treating GI illness (Nichter, 1988). During follow-up interviews, we asked individuals how being sick with diarrhea affected their hydration strategies. The majority of interviewees stated they reduce intakes of every dietary item, including food, fruits, raw water, chicha, sodas, and mixed raw water because consuming more worsens the condition. However, several participants indicated consuming fermented manioc chicha and sodas helps treat diarrhea, and two participants indicated they increase raw water intake when sick with diarrhea. While sodas present significant sources of sugar and calories that are associated with weight, fat gain, and risk of diabetes when consumed excessively (Popkin et al., 2006), in this context they are also a source of clean water, regulated by factory standards. Therefore, individual hydration strategies may be part of a cycle, where they are both related to but also affected by GI illness.

Finally, this study does not account for oxidative water processes, so the total water intake estimates in this paper could be up-revised by ~200-350 ml per individual (Vivanti, 2012). This paper presents water intake levels rather than hydration status and thus cannot address with certainty whether the water intake levels found here are sufficiently meeting needs. Future research should assess hydration status in conjunction with food and fluid intake to fill this gap.

Conclusions

This paper reported that a sample of Tsimane' adults use diverse environmental water sources and that hydration strategies rely heavily on foods. As water recommendations become exported to developing countries, recommendations should be region specific as access to clean water varies and estimates from industrialized countries can under- or over-estimate water needs. High levels of waterborne pathogens create a context where complex strategies must be developed to acquire clean water. While water intake from untreated surface sources are likely leading to infection with GI illness in this sample, increased intake of water from foods may decrease the risk of GI illness. Most notably, individuals consuming high levels of water from foods (43%-73%) had markedly lower probability of GI illness. These findings suggest that people living in areas without clean water may use water-rich foods as dietary adaptations to reduce exposures from dirty water.

Changes in hydration strategies are particularly important to understand because when individuals shift their intake from clean (i.e., food and fruits) to dirtier (i.e., river) water sources when sick, it may create a cycle of illness. Future studies should consider how current and past nutrition transitions affect hydration strategies and water needs since shifts in dietary intake and food preparation, i.e., fruits to grains, may yield net declines in water intake from foods (Vivanti, 2012). Finally, research is needed to corroborate these findings and examine hydration strategies among children, the most vulnerable population to diarrheal diseases.

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Table 3.1: Tsimane' adult sample characteristics and descriptive statistics of water intake.

	Men (n 22)		Women (n 23)	
	Mean	SD (Range)	Mean	SD (Range)
Age (years)	39.5	19.3 (18-77)	36.4	15.3 (17-68)
Height (m)	163.5	5.3 (154.3-175)	153.9	5.8 (143.5-165)*
Weight (kg)	61.9	6.9 (47.3-71.6)	61.4	12.7 (47.3-90.3)
BMI (kg/m^2)	23.1	2.0 (17.0-26.8)	25.8	4.5 (20.4-36.6)*
GI Illness (% reporting)	9%		17%	
Water from foods (liter)	2.4	1.4 (0.18-5.2)	2.3	0.85 (1.1-3.6)
Raw water (liter)	0.90	0.56 (0-1.9)	0.98	0.51 (0.12-2.4)
Mixed raw water (liter)	0.58	0.74 (0-2.7)	0.49	0.59 (0-2.1)
Chicha (liter)	0.98	1.29 (0-3.9)	0.61	0.84 (0-2.1)
Market beverages (liter)	0.13	0.29 (0-1.1)	0.11	0.33 (0-1.5)
Total water intake (liter)	4.95	1.74 (2.4-8.3)	4.43	1.32 (2.0-6.7)

* $p<0.05$, using two-tailed t-test.

Table 3.2: Description of dietary sources with high water contents reported by Tsimane' adults in this sample during 24 h diet recall. Percent reporting and average number of times each item was listed per participant in parentheses.

1. Foods (water content per 100g)	2. Raw water (source)	3. Mixed raw water (with)	4. Chicha (Type)	5. Market beverage (Type)
Plantain - 67 g (98%; 2.53)	River (49%; 3.05)	Powdered flavoring (22%; 0.38)	Manioc (33%; 0.98)	Soda (various) (13%; 0.16)
Rice - 69 g (89%; 1.53)	Hand pump (33%; 3.2)	Sugar (18%; 0.18)	Plantain (18%; 0.24)	Chocolate milk (2%; 0.02)
Fish - 71 g (56%; 1.13)	Stream (13%; 2.83)	Sugarcane (16%; 0.2)	Maize (7%; 0.11)	Beer (2%; 0.02)
Yuca - 59 g (44%; 0.58)	Well (4%; 3.5)	Grapefruit (9%; 0.09)	Plantain/maize (2%; 0.02)	Grain alcohol (2%; 0.02)
Sugarcane - 75 g (33%; 0.56)		Chive (7%; 0.24)		
Papaya - 88 g (22%; 0.31)		Lemon (2%; 0.02)		
Banana - 75 g (11%; 0.11)				
Orange - 86 g (9%; 0.2)				

Water content of foods from the Bolivian Food composition tables 2005 and USDA nutrient database.

Table 3.3: Reported illnesses and symptoms of Tsimane' adults in sample.

Illness or symptoms reported	Number (percent)
Flu/cold (sore throat/ fever/ cough)	16 (36%)
General malaise (body aches/ internal pain/ bone pain)	11 (24%)
Gastrointestinal (diarrhea/ stomach ache/ vomiting)	6 (13%)
None	12 (27%)
Total	45 (100%)

Table 3.4: Logistic regression of water intake from foods and raw water on odds of reporting gastrointestinal illness among Tsimane' adults.

	GI Illness							
	Model 1		Model 2		Model 3		Model 4	
Independent Variables	OR	95% CI	OR	95% CI	OR	95% CI	OR	95% CI
Percent water intake from foods	0.94*	0.89-0.99	0.91*	0.83-1.00	------	------	0.92*	0.85-0.99
Water intake from raw sources (per 100ml)	------	------	------	------	1.12*	1.00-1.24	1.11*	1.00-1.24
Age (years)	------	------	0.97	0.85-1.10	0.99	0.92-1.08	0.97	0.86-1.10
Sex (1=male)	------	------	0.30	0.06-1.49	0.81	0.20-3.21	0.41	0.06-2.88
BMI	------	------	1.12	0.72-1.73	1.17	0.84-1.63	1.15	0.81-1.64
n (Pseudo R^2)	45 (0.15)		45 (0.25)		45 (0.08)		45 (0.28)	

* $p<0.05$. Robust standard errors are adjusted for 23 clusters in household. All models include a constant term.

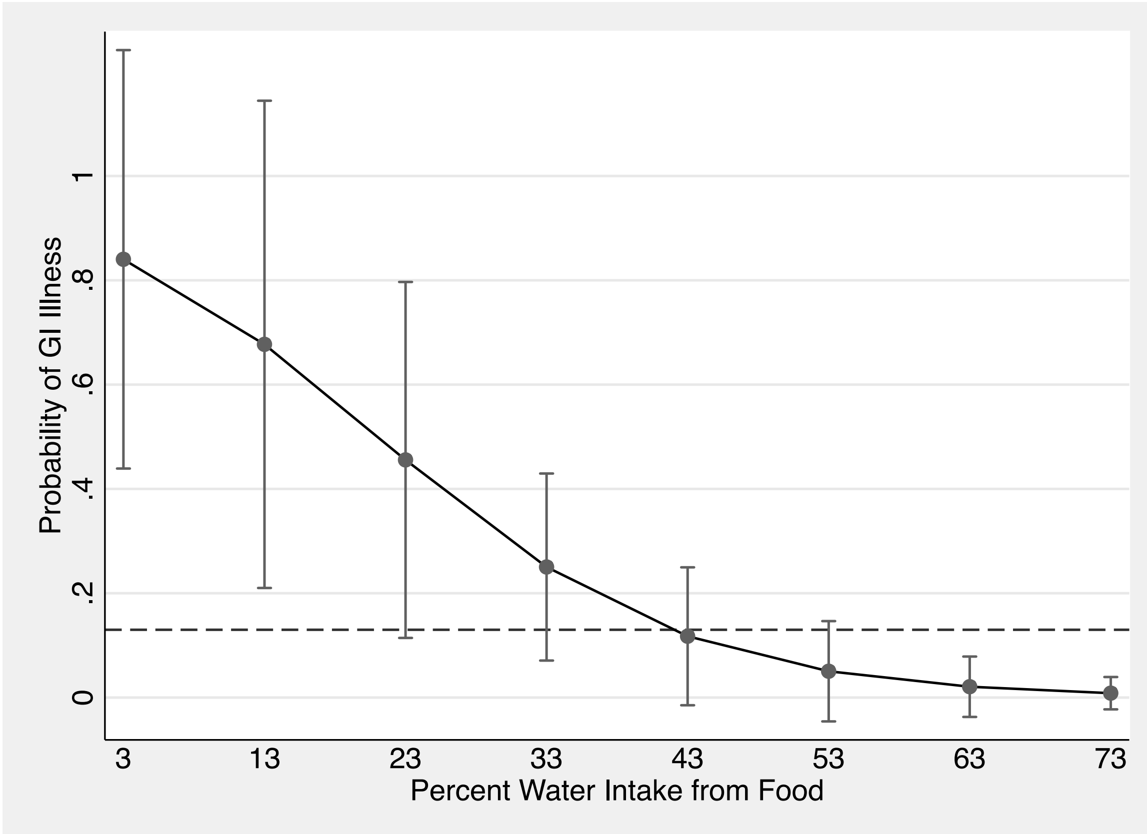

Figure 3.1: Margins plot using coefficients and means from Model 4 in Table 3.4 within range of data reported in this sample indicating probability of GI illness in adults by percent water intake from food with 95% confidence intervals at each margin. Reference dashed line shows sample prevalence of GI illness in sample (13%).

CHAPTER 4

HEAT AND HYDRATION STATUS: PREDICTORS OF REPEATED MEASURES OF URINE SPECIFIC GRAVITY AMONG TSIMANE' ADULTS IN THE BOLIVIAN AMAZON[2]

[2] Rosinger, A. To be submitted to *American Journal of Physical Anthropology*.

Abstract

Earth's climate is projected to exhibit increased variability and hotter temperatures in the 21st century. Populations in developing countries are expected to bear the brunt of the resulting health effects, especially those experiencing rapid lifestyle transitions. Hydration status is critical to physiological and cognitive health, yet it is unclear how populations living in hot-humid environments experiencing transitions manage this underexplored facet of heat adaptation. This study assesses the predictors of hydration status of adults from two villages (close and distant from a market town) selected for variation in market integration in the hot-humid Bolivian Amazon. I conducted interviews and focal follows with 36 Tsimane' (50% male) and collected pre-interview and post-follow urine samples and anthropometric measurements between September 2013 and January 2014. Urine samples were analyzed for urine specific gravity (USG), a biomarker of hydration, with a hand-held digital refractometer. The mean USG was 1.020 g/ml (SD ± 0.008) with men (1.022 ± 0.008) slightly more dehydrated than women (1.018 ± 0.007). Using 1.020 as the criteria for clinical dehydration, 42% of the participants were dehydrated at both intervals. Controlling for time, activity level, anthropometrics, sex, and diarrheal illness in random-effects linear regression models, each degree centigrade increase was associated with an USG increase of 0.001 g/ml (p=0.000). Dehydration was predicted to occur at 29° C, just above the thermoneutral range. While hydration status was tightly connected to temperature, adults from the close village were significantly more dehydrated than those living in the distant village. These findings suggest that hotter temperatures coupled with lifestyle transitions may create conditions that increase vulnerability to dehydration among rural populations.

Introduction

The Inter-Governmental Panel on Climate Change (IPCC) projects that the South American climate, similar to many other regions, will exhibit increased variability and hotter temperatures in the 21st century (Magrin et al., 2014). Extreme temperatures can contribute to dehydration, heat-related illnesses (heat stroke), and death (Luber and McGeehin, 2008). Several aspects of human heat adaptation and heat tolerance, such as sweat rates, blood flow, skin temperature, and heart rates, have been examined in different microclimates because responses to heat are critical to physiological functioning and homeostasis (Adolph, 1947; Fox et al., 1967; Hanna and Brown, 1983; Wheeler, 1993; Patterson et al., 2003; Taylor, 2006; Steegman, 2007). Hydration status, the internal state of water balance within an organism, is a major component of human responses to heat that has not received adequate attention outside of laboratory or athletic studies examining performance (Armstrong et al., 1997; Casa et al., 2010; Garrett et al., 2014).

While humans are a widely adapted species living in virtually every ecological niche on earth with local adaptations and use different strategies to extract enough water to survive, Lieberman (2015:99) states that "all human populations are variants of a basic adaptive pattern for long-term aerobic exertion in hot habitats." Yet, climate change will likely have the largest impact on the health and daily life of populations who are undergoing lifestyle transitions (defined as changes in physical activity, settlement patterns, housing, and participation in national economic markets) (Magrin et al., 2014). This will be especially true among those with little infrastructural or governmental support and live in conditions where exposure to environmental temperatures is high, thereby increasing vulnerability to heat-related morbidity (Barkey et al., 2001; Lundgren et al., 2013). Populations experiencing the early period of lifestyle transitions enduring environmental pressures and changes in diet and landscape may be experiencing an evolutionary mismatch, which is significant to physical anthropology and human biology because it may extend our understanding of thermoregulation and key factors that led *Homo* to develop adaptations like voluntary dehydration and decoupling thirst from hydration (Noakes, 2010; Hanna & Brown, 1983).

In the present paper, I examine daily hydration patterns of adult Tsimane' forager-horticulturalists from two villages selected for variation in market integration (one close and one distant to a main market town) in the hot-humid Bolivian Amazon. I then examine the relationship between ambient temperature, lifestyle, and physical activity on hydration status to understand what drives these daily rhythms using human adaptability as a primary theoretical lens.

Adaptation to the Hot-humid microclimate

Physical anthropology has a long history of examining adaptations to the thermal environment, which has been proposed as an important selective factor during the evolution of *Homo* through a myriad of traits including body shape, distribution and types of sweat glands, body hair, and skin color (Hanna and Brown, 1983; Wheeler, 1993; Jablonski, 2004; Noakes, 2010; Wells, 2012). The hot-humid microenvironment, present in much of the tropics, raises a key dilemma in the human physiological response to heat, namely the reduced effectiveness of sweat evaporation to cool the body (Hanna and Brown, 1983), thereby increasing stress on the homeostatic hydration process.

The main physiological adaptation to humid heat is the combination of cutaneous vasodilation and a ready onset of sweating (Taylor, 2006). In a review of genotypic versus phenotypic heat adaptation, Taylor (2006) generalized that native populations in hot-humid environments had lower skin blood flow and higher skin temperature (to buffer heat gains) leading to more efficient evaporation of sweat and reduced sodium loss compared to non-indigenous, which is ideal in hot-humid environments. Hanna and Baker (1974) noted that Shipibo Indians had lower increases of heart rates with rising temperature yet actually sweated more at moderate levels of activity in comparison with a heat acclimatized mixed population in the hot-humid Peruvian Amazon. However, many of the early adaptability studies did not measure hydration status alongside these other variables of heat tolerance (Frisancho, 1993). These differences in heat tolerance may confer advantages that would be translated to better hydration in high temperatures.

Many adjustments to humid heat are behavioral and cultural rather than physiological or genetic (Hanna & Baker, 1974; Ladell, 1964; Frisancho, 1993). Settlements are often built near a water source to take advantage of wind flow. Minimal clothing allows for maximum skin surface available for sweat evaporation and either open or closed housing is used to cool or warm interiors. Behavior follows a pattern to reduce exposure to heat with work beginning in the early morning, then midday rest followed by moderate work (Hanna & Baker, 1974; Moran, 2008).

Yet, these work patterns and other behavioral adaptations still often result in voluntary dehydration (Ulijaszek, 2001). The phenomenon of voluntary dehydration has long been observed in humans, where workers and athletes do not consume enough water to replenish lost fluids during work or exercise (Hanna and Brown, 1983; Ulijaszek, 2001). Noakes (2010) contends that voluntary dehydration and uncoupling thirst from hydration status is evidence of an evolved human response to water scarcity. Citing the Ju/'hoansi San's endurance or persistence hunting technique, Noakes (2010) states that humans are able to deal well with dehydration without severe consequences and rehydrate later. If humans were not able to voluntarily dehydrate, meaning that they immediately felt the symptoms of dehydration even at low levels, then productivity would decline because they would be constantly seeking rehydrating beverages and foods. It is possible that the hot-humid environment is another environmental selective pressure that facilitated the development of voluntary dehydration.

Hydration status, temperature, and lifestyle transitions

Hydration status is fundamental to understand in relation to adaptation to heat stress because dehydration adversely affects aerobic exercise tasks by increasing heat storage and decreasing sweat rates, thereby reducing the body's ability to lower core temperatures and increasing heat strain (Sawka et al., 2001). Mild dehydration is defined as a loss of 1-2% of body weight as a result of fluid loss, while a loss of greater than 3% is severe dehydration (Kleiner, 1999). Ambient temperature and physical activity change water needs (Sawka et al., 2005). Welch (1958) found that active men in 30° C or higher consumed, on average, 6 liters (L) of water a day compared to the recommended 3.7 L for men by the Institute of Medicine (2004).

Moreover, an individual's response to temperature interacts with their internal state of hydration (Sawka et al., 2011). In a review of the effects of dehydration on physical performance in different environmental conditions, Shirreffs (2006) showed that dehydration of 2% or greater in hot environments (30°C+) causes more of a deficit to performance (measured through running times) than in warm (22° C) or cold (5-10° C) environments. Additionally, exercise in hot but not thermoneutral (25-27° C) and cold environments coupled with dehydration is associated with increased heart rate and increased core and skin temperature leading to cardiovascular strain and reduced stroke volume (Gonzalez-Alonso et al., 2000; Kenefick et al., 2004).

A significant amount of research has demonstrated the physiological and cognitive repercussions of dehydration. Dehydration has long been tied to decreases in physiological function as it affects proper internal temperature regulation during activities (Sawka et al., 1998;

Murray, 2007). More recently, dehydration at levels as low as 1.5% and greater are associated with decreases in short-term memory, arithmetic efficiency and ability, visual-motor tracking, and attention, while increasing perceived fatigue (Grandjean and Grandjean, 2007; Lieberman, 2007; Ganio et al., 2011; Armstrong et al., 2012).

Maintenance of hydration status is one of the most effective strategies to protect individuals exposed to heat or exercise stress, yet people have different histories of exposure to heat (Maughan and Shirreffs, 2008). In fact, it is possible to lose many of the characteristics associated with heat-acclimatization after prolonged time away from the hot-humid environment. Lee et al. (2004) described this phenomenon, known as heat-deacclimatization, by showing that duration of stay in Japan by native Malaysians was associated with shorter onset time of sweating and higher sweat volume at lower temperatures when compared to native Malays. This research illustrates that human heat adaptation is a flexible process as the phenotype interacts with the environment. Yet, Fleming and James (2014) illustrated that in a controlled environment, repeated familiarization with dehydration reduced the deleterious performance effects of dehydration, most likely through attenuated perception of intensity. Therefore, it is possible that the homeostatic process of hydration is subject to environmental phenotypic modification.

Interestingly, many populations who are undergoing lifestyle transitions (nomads being settled, rural populations integrating into market economies) report health complaints that are consistent with symptoms of dehydration, including headaches, anxiety, and fatigue (Barkey et al., 2001; Izquierdo, 2005; Tanner and Rosinger, 2014). Yet, little recent research has examined hydration status among native populations undergoing lifestyle transitions (Kleiner, 1999). Coincidentally, many transitioning populations do not have access to potable water and suffer from high rates of diarrheal and parasitic infections (Barkey et al., 2001; Tanner et al., 2013; Cepon-Robins et al., 2014), which make them highly vulnerable to chronic dehydration.

Lifestyle transitions have resulted in rapid changes in environment, work patterns, and diet, which change the dynamics of nutrition, body composition, and health (Baker et al., 1986; Lourenco et al., 2008; Sorenson et al., 2009; Valeggia et al., 2010; Rosinger et al., 2013). These rapid shifts make it an ideal setting to study hydration status because hydration is a homeostatic process that balances environmental stresses, work, and disease load. Examining hydration in native populations in hot-humid environments, like other previously studied physiological mechanisms, during lifestyle changes may provide a window into human adaptation and adaptability to temperature because traditional buffering mechanisms, such as diet and activity scheduling may be disrupted (Baker et al., 1986).

Furthermore, examining hydration status among a native Amazonian population in transition may provide clues about the role climate change will play in this relationship in the coming century. The present study tests three environmental and lifestyle predictors related to hydration status: 1) Higher temperatures will be associated with a less hydrated status adjusting for body size because of increased heat load; 2) Physical activity levels will modify the relationship between heat and hydration status; and 3) Individuals experiencing lifestyle transitions more acutely will be at greater risk of dehydration, by comparing a close and distant village at opposite extremes in integration to the market as a proxy for lifestyle transitions.

Methods

Fieldsite and Background

The Tsimane' territory lies 50 km east of the Andean foothills, approximately 14°5' south to 15°5' south latitude and between 66°5' and 67°5' west longitude. This region is located in the lowland department of the Beni, one of nine departments in Bolivia. Tsimane' number approximately 15,000 in 100 villages, with the majority of villages on the banks or tributaries of the Maniqui River. Tsimane' have been noted as a native population living in this region since before 1621, when the first mention of them was made by a Franciscan Priest, Gregorio de Bolivar (Nordenskiold, 1979[1924]). Four hundred plus years is sufficient to develop characteristics associated with a hot-humid climate (Moran, 2008).

High stable average temperatures (26.8 °C average yearly temperature), high humidity, and high rainfall (1,743 mm mean rainfall) characterize the climate in this region (Godoy et al., 2008). The year is split into a dry season from May to October and a wet season from November to April. Past research has shown that variability of rainfall during early childhood among Tsimane' girls, but not boys, has a negative effect on female adult height (Godoy et al., 2008). Tsimane' men and women have an average adult height of 163 cm and 151 cm, which is short when compared to US and industrialized populations, but taller than several other lowland South American Indian populations, such as the Machiguenga, Ache, Hiwi, and Tukano (Godoy et al., 2006). The average BMI of Tsimane' adults in 40 randomly selected communities in 2008 was 23.6 kg/m^2 (Rosinger et al., 2013), but has increased steadily between 2002 and 2010 (Rosinger & Godoy, 2015).

Tsimane' have moderately active to vigorously active lifestyles with physical activity levels (the ratio of total daily energy expenditure to daily basal metabolism) of 1.73 for females and 2.02 for males (Gurven et al., 2013). Men spend a significant amount of time working in their slash and burn fields, fishing, and hunting, while women tend to domestic work, such as cooking, getting firewood, fetching water, and childcare, as well as helping in the fields and fishing (Ringhofer, 2010). Their activity patterns are characterized by methodical work in the fields rather than short bursts of heavy labor. Their physical activity levels are on par with other subsistence populations, but higher than averages from industrialized countries (Gurven et al., 2013). The health profile of Tsimane' is characterized by high rates of infectious diseases, in the forms of intestinal parasitism (56-80%) and diarrhea (Gurven et al., 2007; Blackwell et al., 2011; Tanner et al., 2013; Tanner and Rosinger, 2014).

Tsimane' have begun to undergo lifestyle transitions in the past 30 years through participation in the Bolivian market economy, cash cropping, and buying market products. These lifestyle transitions are described elsewhere (Godoy et al., 2009; Rosinger et al., 2013). A recent study found that Tsimane' adults consume significantly more water [4.6 liters per day (lpd)] than adults in industrialized countries (2.4 – 3 lpd) and that approximately 50% of their water intake comes from food sources (Rosinger and Tanner, 2015). As more water from food was incorporated into their hydration strategies, the risk of diarrhea decreased significantly. However, that study did not measure hydration status and so it is unclear whether the high levels of water intake were sufficiently meeting water needs. Together, the physically active but changing lifestyle, disease ecology, and hot-humid climate are demanding for water needs and make dehydration likely.

Study Communities and Sample

This is part of a larger study aiming to understand water and hydration among Tsimane'. The phase of the research reported here took place in 2 communities: September-October 2013 in a close village to the main market town of San Borja and December 2013-January 2014 in a distant village to the market town. The two research communities were selected to provide variation in distance to the main market town, market participation, and lifestyle. The close village is an hour car ride to the main market town of San Borja during the dry season or a 2-3 hour motorized canoe ride during the wet season, and it has five primary water sources (river, stream, pond, handpumps, and wells). The distant village is a two-day motorized canoe ride away from San Borja year-round and only has access to the river and stream for water sources. The distant village exhibited a more traditional lifestyle and diet than the close village. Members from the close village engaged in cash cropping as their primary livelihoods strategy, selling excess plantains, yucca, rice, and maize in the market; whereas individuals from the distant village had much smaller slash-and-burn horticultural fields that provided food only for household consumption. Individuals from the distant village hunted and fished more, extracted forest products, like jatata (a palm-thatch), and did not buy as many market products as individuals in the close village. This difference in size of horticultural fields is characteristic of differences between more integrated, closer villages and less integrated, distant villages. Vadez and Fernandez-Llamazares (2014) illustrated that more integrated villages on average have fields that are 57% larger than less integrated villages.

The sample consisted of 36 adults (18 men, 18 women; avg age 38.7 [14-80, 19.2 SD]) in two villages (see Table 4.1 for sample characteristics). Age was measured by asking individuals their birthdate, how old they were, and verified with a birth certificate when possible. Only household heads were interviewed, alternating between the head male and female to provide a 50-50 sex breakdown. Because the close village was larger (59 households), the village was broken into 5 geographic sections and, within each section, four to five households were selected based on age, sex, and relationship to neighbors (yielding an n of 21). In the distant village, exhaustive sampling was attempted and 15 of 16 households were sampled (one household was absent). Permission was granted by the Grand Tsimane' Council, village leaders, and each participant gave oral consent before data collection. The Institutional Review Board at the University of Georgia approved the study protocol (IRB #2012-10290-0).

Interview and observation periods

This observational study was designed to capture daily fluctuations in lifestyle, temperature, and hydration status in a natural environment. Overall, it consisted of a qualitative interview immediately followed by a ~3 hour focal-follow period where activities were recorded in 5-minute increments (Obrien, 1998). Additionally, the author collected anthropometric measurements, ambient temperature, and a urine sample to determine hydration status both before the interview and after the focal-follow. This study design provided a total of 2 urine samples per person and a total of 4 periods sampled throughout the day while participants had access to ad-libitum food and water. To avoid confounding of sex-time activity patterns, 10 of 19 morning interviews and 8 of 17 afternoon interviews took place with women.

Qualitative interviews lasting between 30 and 55 minutes occurred in the morning (beginning between 8:00-9:00 am) and afternoon (1:30-2:30 pm) and covered topics regarding diet, thirst, dehydration, hydration strategies, and diarrhea treatments. During the interview, participants were asked if they were suffering from diarrhea currently (defined as three loose stools in 24 hours) because diarrhea is associated with dehydration. If women were observed breastfeeding or answered that they were breastfeeding, they were noted as breastfeeding. Urine samples were collected for each individual before the beginning of the interview or as soon as possible (two individuals produced a sample during the interview) and at the end of the focal follow (generally between 11:30am-12:15 pm, and 4:30-5:30 pm). The samples were covered and placed aside to cool before reading. Before the interview and following the focal follow, the height of each individual was measured using a standing stadiometer, rounded to the nearest 0.1

cm (Seca 213) and weight, percent body fat, and percent total body water measured using a Tanita Bioimpedance scale (0.1 kg).

Hydration status and dehydration

Daily hydration status has been described as a sinusoidal wave that is constantly in flux (Armstrong, 2007). I used urine specific gravity (USG), or the density of urine compared to the density of water, to measure hydration status. While there is no gold standard for assessing hydration status, USG is noted as the best indicator for field measurements (Armstrong, 2007). A significant amount of research has evaluated USG as an indicator of hydration status and found that it is a good biomarker of hydration, is sensitive to dehydration, provides instant assessment of hydration levels, is highly correlated with other measures of hydration, portable, and easy to operate, especially when using a refractometer (Stuempfle and Drury, 2003; Oppliger et al., 2005; Armstrong, 2007; Armstrong et al., 2010). USG was analyzed using a digital hand held refractometer (Atago – Pen Refractometer, Measurement accuracy ±0.0010; resolution 0.0001), which was calibrated daily with bottled water. Urine samples were discarded after the reading. Each sample was read 3 times with the majority reading recorded. First morning urine has higher density, is more concentrated than other urine samples throughout the day, and overestimates dehydration (Armstrong et al., 2010). For this reason, when collecting urine for period 1, urine samples were collected after a first morning urine sample was voided.

While USG is a continuum, with a general range between 1.000 and 1.040 g/ml, values above 1.020 are an accepted cut-off point for clinical dehydration (Armstrong et al., 2012). Oppliger et al. (2005) found an association of 3% body mass loss associated with a USG of 1.020. A significant amount of research has evaluated the USG cutoff of 1.020 as a measure of dehydration because the National Collegiate Athletic Association (NCAA) set these levels as mandatory for participation in wrestling events (Stuempfle and Drury, 2003; Oppliger et al., 2005; Stover et al., 2006).

Ambient Temperature

Ambient temperature was measured through an indoor/outdoor wall thermometer placed in the shade at the interview site (Springfield Precision #90116). Temperature was recorded at each urine sample and rounded to the nearest 0.5° C. Conducting the focal follows over a span of 5 months provided adequate variation in temperature, which is sometimes difficult in the humid tropics (See fig. 4.1 for temperature distribution). For example, southerly windstorms lasting 1-4 days, or "Surs," cause cooler than normal temperatures, once dipping below 20° C during the research period.

Activity Levels

Following James and Schofield (1990) and FAO/WHO/UN (1985), I used a modified and simplified method similar to the factorial method to estimate short-term physical activity for periods of 2-4 hours based on observed and reported activities. Activities were classified into a categorical variable of light, moderate, and heavy for the time period leading up to the first urine sample based on activity recall collected during the interview and then for the time period of the focal follow based on direct observation following Nag et al. (2007). See table 4.2 for examples of the activity classification breakdown.

Statistical analysis

Data was analyzed in Stata 13.1 (College Station, TX). USG was normally distributed in the sample and no transformations of this data were performed. Bivariate associations between USG and covariates of interest were analyzed through Pearson's and Spearman's correlations, two-way t-tests, one-way ANOVAS, and scatterplots. I then estimated effects through generalized least squares (GLS) random effects (RE) estimators because time invariant variables exist during one day of observations (sex, diarrhea, village membership). The RE model is estimated as follows:

$$Y(\text{USG})_{it} = \beta_{0it} + \beta_1 \text{Village}_i + \beta_2 X_{it} + \beta_3 T_t + u_{it} + \varepsilon_{it}$$

where Y denotes the urine specific gravity of each participant i in time period t; $B1$ is the dummy variable to test for differences between villages; X_i is a vector of environmental covariates (most notably ambient temperature) and individual covariates like activity levels; T are period sampled dummy variables; u is the between entity part of the error term, and ε is the within-entity error.

To control for the confounding effect of period sampling on temperature as temperature rises along with the period sampled during the day, I included dummy variables for each sampling period in all models reported. For sensitivity analysis, I estimated a fixed effects (FE) model and conducted a Hausman test, which tests the null that the unique error terms are correlated with the regressors (Wooldridge, 2009). I fail to reject the null ($p=0.24$), meaning that the RE models are more suitable to the data in this case than FE models. To test for robustness of results, I ran a RE logit model with USG dichotomized at 1.020 to see if the effects remained when examining the outcome of dehydration (Wooldridge, 2009).

<u>Results</u>

Salience of dehydration to Tsimane'

During the interview, participants described dehydration (*chanej*), thirst (*jari'rij*), and how frequently they experienced these sensations. The Tsimane' word *chanej* literally means "dry" and is applied to physical symptoms among humans, like a dry throat or dry body, but also to plants and soil, when they do not receive enough water. On the other hand, Tsimane' describe thirst or *jari'rij* in the context of short-term sensations when an individual wants something to drink because she feels thirsty.

When asked to describe symptoms or attributes of *chanej,* individuals listed having headaches, fatigue (*nobi*), and very commonly a lack of "force" or "will" to work. Additionally, every interviewee stated that dehydration was common and experienced most days, though, this depended on his or her activities and if it was a sunny day. One woman stated: "I feel dehydrated 10 times a day sometimes - when I work hard and it's hot. Five times when I stay here at home." The most common response was feeling dehydrated two to three times in a day. Thirst was described similarly to dehydration. When asked about thirst, one participant stated: "There's thirst always, everyday." Participants indicated that dehydration though was more serious than thirst.

Descriptive and Bivariate analysis

Tsimane' adults are relatively dehydrated compared to U.S. standards. The average USG was 1.020 (SD ± 0.008) for the sample, with values higher for men than women, 1.022 (± 0.008) vs 1.018 (± 0.007) ($p=0.034$; t-test). Forty-two percent of the 72 samples were above the cutoff level of 1.020 indicating dehydration. When the samples were averaged, 50% of adults were dehydrated. Twenty percent of participants had a USG of 1.030 or higher, classified as severe dehydration. Overall, USG did not change significantly between the two urine samples (USG $\Delta=0.0015$; $p=0.42$; t-test). Only six individuals moved from a hydrated to a dehydrated state or vice versa between the two samples (50% each direction; Table 3). However, the largest change observed for one individual (a young lactating woman) was a USG value of 1.012 in sample 1 which increased to 1.028 in sample 2.

Ambient temperature was highly associated with USG for the sample (Pearson's R = 0.66; p=0.000). The temperature average during the study was 27.7° C (range 17°-37.5°). Figure 4.1 illustrates the strong linear relationship between temperature and USG for both sexes. However, men crossed over the dehydration cutpoint at a lower temperature than women. Mean ambient temperature did not differ between the two villages [28.2 C (close) vs 27 C (distant); p=0.27; t-test].

The sampling period was also significantly related to USG for the sample (Anova F=6.7; p=0.001). Figure 4.2 illustrates that there is an increasing trend through the first 3 periods that levels off at period 4, and, on average, participants met the criteria for dehydration between periods 2 and 3. Men and women differ, on average, in hydration status throughout the day. In the sample, average USG for men increases substantially between time period 1 and 2 from 1.017 to 1.022, then increasing again at period 3, before leveling off in period 4. For women, the average values of hydration remained in a euhydrated state during the first two periods, but increased significantly at time 3 to 1.022. Nevertheless, the correlation between sampling period and USG is likely due to rising temperatures as the period was highly correlated to temperature (Spearman's Rho = 0.50; p=0.000; Anova F=8.3; p=0.001). Average temperatures per sampling period are shown by sex and by village in figures 4.2 and 4.3, respectively.

Body size measures, such as height (p=0.39), weight (p=0.99), and BMI (p=0.31), were not significantly associated with USG. Two anthropometric measurements, body fat (Pearson's R = -0.33; p=0.005) and total body water (Pearson's R = 0.34; p=0.004) [which are highly inversely correlated with each other coming from the Tanita scale (r=-0.96)] were significantly associated with USG. Lactating women (USG = 1.019, 42% dehydrated) (12 of 18 women) did not have significantly different hydration levels than non-lactating women due to lack of power

(USG=1.016, 17% dehydrated) (p=0.19, t-test). Only three cases of diarrhea were reported among the 36 adults, which was not associated with USG using a t-test (p=0.39). Finally, age was not associated with hydration level (Pearson's R = -.14; p=0.25).

Activity levels reported for the time period before the focal follow and observed during the focal follow were positively associated with USG levels (Anova F=3.05; p=0.054). Individuals who were dehydrated at the time of the first sample had significantly higher activity levels leading up to the urine sample than euhydrated individuals (activity level of 2.1 vs 1.2; t-test t=3.72; p=0.001). At the second urine sample, the effect was attenuated. Individuals who were dehydrated at the second sample were not more active during the focal follow than those who were euhydrated (activity level of 1.3 vs 1.2; t-test t=0.69; p>0.05). Finally, activity levels did not differ by village [activity level of 1.4 (close village) vs 1.5 (distant village); t-test t=-0.50; p=0.62].

Village membership was significantly associated with hydration levels. Interestingly, adults from the close village were significantly more dehydrated than adults from the distant village, 1.022 vs 1.018 (p=0.01; t-test). Individuals in the close village began the day in a more dehydrated state than individuals in the distant village and this difference continues throughout the sampling periods (Fig. 4.3).

Random effects linear regression

Results of the RE models are presented in Table 4.4. In model 1, controlling only for period sampled (time of day: 8 am, 12 pm, 2 pm, 5 pm), the average effect of each degree centigrade between the two samples is associated with 0.0009 higher USG (p=0.000). Model 2 indicates that individuals in the close village were significantly more dehydrated than individuals from the distant village (p=0.041), yet temperature remained significantly associated with USG (p=0.000; 95% CI 0.0005, 0.0013). The effects of village residence and temperature remained robust to alternate specifications of the models when controlling for period sampled, sex, activity level, diarrhea, and anthropometrics (Model 3-6).

The moderate activity level was positively associated with USG in models 3-6, yet the association between the high activity level and USG was not significant. An interaction term of temperature and activity level was not significant (results not shown). Models 4-6 adjusted for measures of body size but no significant results were found in the relation between body composition and hydration levels. While only 3 individuals reported diarrhea, it was positively associated with USG in 3 of the 6 models. The overall R^2, which is a weighted average of between and within entity estimators for the model, ranged between 0.46 and 0.60 in the 6 models presented.

Robustness

I conducted two additional tests of robustness. First, I examined when individuals would cross over the point of dehydration. I estimated the average effect of temperature on USG for the sample adjusting for covariates by using the predicted values from model 3 (the model that includes all participants with the highest overall R^2) presented in Table 4.4 generated by the margins command in Stata (results not shown). This test found that dehydration is predicted to occur for the sample when the temperature reaches 29° C or higher.

Next, to evaluate if ambient temperature and village residence were associated with increased probability of dehydration, I created a dichotomous variable for dehydration following the values set by Oppliger et al. (2005) with USG>1.020. I reran the analysis as a non-linear RE regression (xtlogit) with the same covariates in model 3. Consistent with results presented in Table 4.4, each degree centigrade is significantly associated with higher risk of dehydration

(Odds ratio=2.12; 95% CI 1.04, 4.32; full results not shown). This result was robust to alternate specifications (results not shown). However, while the distant village did have lower odds of dehydration than the close village, village residence was not significantly associated with odds of dehydration (OR= 0.24; 95% CI 0.01, 6.36; results not shown).

Discussion

I structure this discussion around four main findings. First, I review how Tsimane' hydration levels compare to U.S. populations and guidelines for dehydration. Second, I discuss how temperature is associated with hydration status and the implications of changing weather patterns and higher temperatures and the role of hydration status in heat adaptation. Third, I discuss how activity levels relate to this association and relate it to the phenomenon of voluntary dehydration. Finally, I discuss the relationship between lifestyle transitions and hydration.

Overall, the USG values found in this sample were slightly higher than values found by research conducted in the U.S. Stover et al. (2006) found that recreational exercisers in the U.S. had an average pre-exercise USG level of 1.018. Armstrong and colleagues (2010, 2012) examined healthy U.S. young adult men and women to set reference values of hydration status and found that roughly 40% of both samples had values above 1.020. The average USG in this sample of Tsimane' adults was 1.020, close to the cutoff for dehydration. Overall, 42% of participants met the clinical criteria for dehydration, while 20% of the participants were severely dehydrated with USG values above 1.030. The present study suggests that close to half of the adults in this sample had difficulty maintaining a well-hydrated state throughout the day. This finding is in line with other research that predicts dehydration for farmers in tropical environments due to high heat and humidity stress (Nag et al., 2007). The propensity to become dehydrated during the day may not be due to low overall water consumption because a recent study found that a sample of Tsimane' adults consume significantly more water than industrialized populations (4.6 liters vs 3.0 liters in the US) (Rosinger and Tanner, in press). However, this inference must be interpreted with caution because intake information was collected one year before the present study.

Hydration, temperature, and heat adaptation

The results show a strong association between temperature and hydration status adjusting for body size, providing support for prediction 1, that higher temperatures will be associated with worse hydration. When extrapolating the findings, a 2°C increase in temperature (predicted to occur in South America in the 21st century with high confidence, Magrin et al., 2014) would be associated with an increased USG of 0.002 and a 4.4 fold higher probability of dehydration from an average baseline temperature of 27.7. Dehydration is predicted at 29° C in this sample, just above the thermoneutral range (25-27° C) of humans (Leonard, 2012). In many regions, climate control buffers the energy expenditure needed for thermoregulation. Among populations without electricity, air conditioning is unavailable and while hand held fans, activity scheduling, and housing are means of climate control (Moran, 2008), outside the thermoneutral range individuals expend extra metabolic energy to maintain a stable body temperature (Stanier et al, 1984). Therefore, with increasing temperatures, extra stress will be placed on thermoregulatory, metabolic, and hydration processes in the body.

While much has been written in regard to body shape and thermoregulation (Hanna and Brown, 1983; Wheeler, 1993; Wells, 2012), the present study did not find any relation between weight, height, percent body fat, or total body water and the short-term measure of hydration status in the regression models. However, having a smaller body size does on average reduce water needs and metabolic heat production (Wheeler, 1993; Sawka et al., 2005). It is likely that non-heat-adapted adults with bigger bodies would become dehydrated faster than native populations exposed to the hot, humid environment (Hanna & Baker, 1974; Moran, 2008)

The role of hydration may provide additional insights into heat adaptation. Humans exhibit different levels of adaptation to hot-humid environments, from evolutionary and genotypic, to developmental and physiological, to behavioral and cultural adaptations (Wheeler, 1993; Ruff, 1994; Katzmarzyk and Leonard, 1998; Steegman, 2007; Wells, 2012; Lee et al., 2004; Taylor, 2006; Noakes, 2010; Frisancho, 1993). While recent research found that dehydration may enhance an individual's thermoregulatory responses to short-term heat acclimation, these effects may be opposite for long-term heat acclimation (Garrett et al., 2014). Chronic dehydration may in fact negatively affect these responses to heat. According to Garrett and colleagues (2014), humans have not been able to develop tolerance to repeated acute dehydration, such that severe dehydration overrides long-term adaptations to heat. This argument implies that if individuals who have long-term heat adaptations become embedded in a cycle of chronic dehydration, that may be caused by a lack of clean water, holoendemic parasitism, diarrhea, rising temperatures, and an active lifestyle, those adaptations may not provide them the same benefits as those living in a more stable ecology. Future research should further explore how hydration status interacts with these different levels of human heat adaptation.

Activity levels and voluntary dehydration

Results supporting prediction 2, that activity levels would amplify the effect of temperature on dehydration, were mixed. Individuals who were dehydrated at the first urine sample had significantly higher activity levels than those who were not dehydrated, but this effect was attenuated at the second urine sample. Additionally an interaction between temperature and activity level was not significantly related to USG. Women had lower USG than men, but this is likely due to slightly lower physical activity levels as only 6% of women had high activity levels compared to 20% of men. Similar to Gurven et al. (2013) who found that women had a moderately active lifestyle, women in this sample were not as physically active during the focal follows as men. The most common activities observed for women were visiting, childcare, weaving bags while sitting, and cooking, while for men they were working in the field (clearing, cutting, planting), visiting, extracting and carrying palm thatch from the forest and making roof panels of this, called *jatata*. The differences in physical activity levels also likely explain why men became dehydrated at slightly lower temperatures than women (26 vs 29.5 C) (Fig. 4.2). The absence of a significant relationship between lactating and hydration status is due to a lack of statistical power in the sample. A follow up study with a larger sample size found a similar effect size (0.004) to the present study (0.003) that was significant between lactating status and USG and that lactating Tsimane' women were significantly more likely to be dehydrated than non-lactating women (Rosinger, in press).

A potential reason why the relationship between hydration status and the approximation of activity level in the analyses is not stronger is likely due to a lag effect of heavy and moderate work on hydration status. Therefore, if an individual had a medium or high activity level before the interview and focal follow, those dehydrating effects remained regardless of whether they reduced their activity level to light during the focal follow and consumed food and drink. This finding highlights the fact that in a hot-humid environment, it takes a longer time to rehydrate and return to a euhydrated state (Sawka et al., 2011). Previous research has shown that rehydration following severe dehydration takes 18-24 hours (Sagawa et al., 1992).

The author observed that on several focal follows, when men worked in their slash-and-burn fields, or went into the old growth forest, they drank minimal amounts during work.

However, upon returning home, they would gulp a couple of cups of water or *chicha,* a traditional fermented beverage, immediately. This observation echoes the idea of a home base being used for a secure water location (Hanna and Brown, 1983; Wutich and Brewis, 2014). It also suggests that rehydration occurs most effectively at night and early morning when temperatures are cooler and activity levels are lower and helps explain why morning USG levels were consistently lower than afternoon levels.

The hydration patterns observed among this sample of Tsimane suggests that the majority of individuals engage in voluntary dehydration as the average afternoon USG was 1.023, meaning that they did not sufficiently replenish fluids to maintain a euhydrated state during the day. The average observed pattern of USG during the four sample periods illustrated in Figure 4.3 is strikingly similar to Ulijaszek's (2001) models of projected water losses during different scenarios of work scheduling among Australian Aborigines in different climatic conditions. Those models suggested that even utilizing an early morning four-hour work day on overcast days would lead to dehydration, but that water losses are much greater starting the work day later and on sunny days. The present study illustrates how hard it is to remain well hydrated while being physically active in a hot-humid environment, despite cultural and behavioral adaptations along with a lifetime of heat acclimatization.

Lifestyle transitions and dehydration

While the present study relies only on two villages at extremes in the spectrum of integration into the market economy within a homogenous native population in one season, to the author's knowledge, these findings suggest for the first time that another unintended consequence of lifestyle transitions during the early stages may be an increased vulnerability to dehydration. Consistent with prediction 3, adults from the close village had higher USG compared to adults from the distant village adjusting for other covariates previously discussed. These findings support previous research documenting reports of dehydration-related symptoms, like headaches, during transitions (Barkey et al., 2001).

Two potential reasons why lifestyle transitions may increase vulnerability to dehydration relate to landscape modifications and dietary changes. Clearing of forest is common in many parts of Amazonia for cropland and pasture, but has implications for increased solar radiation, reduced wind, and water tables (Defries et al., 2002; Laurence, 2004). Vadez and Llamaz-Fernandez (2014) found that Tsimane' have begun to cash crop, rely on less diversity in their fields, and that village distance to San Borja predicts the size of their fields. Closer villages have significantly larger fields, which have less tree cover. Tsimane' that spend significant amounts of time in these fields are working under the hot sun, whereas, Tsimane' who work under the forest canopy are less exposed to solar radiation. In the present study, individuals in the distant community spent more work time in the forest than individuals in the close community. Solar radiation has been shown to be associated with higher heat stress and leads to higher water losses (Ulijaszek, 2001).

While not explicitly measured in this study, a second potential explanation relates to diet differences between the two communities. Individuals in the close community mixed raw water with sugar for beverages and fried foods more frequently than individuals in the distant community who made the traditional meal of *jona*, a plantain based stew, for the majority of their meals, which have implications for water content (Zycherman, 2013). During 6 months of participant observation in both communities, the author observed individuals in the distant community eating more fruit than individuals in the close community. Previous research indicates that eating fruit for water as well as soups is better for rehydration (Sagawa, 1992;

Potter, 2011). These two facets of lifestyle transitions working in concert may increase vulnerability to dehydration in the early phases of transitions before access to clean water and sanitation is widely available.

Limitations

The present study is subject to several limitations. First, while the researcher explained to individuals that they should proceed as normal following the interview, it is possible that normal activity patterns were affected by the interview, such that some individuals may have preferred to stay around the house and do tasks rather than go work in their fields. This researcher effect would have biased activity levels downward while also providing higher access to water and food present in the house and resulted in lower USG levels. If removed, the effects of temperature and activity may be stronger than the findings reported here. While USG is the best field-friendly measure of hydration status, Oppliger et al. (2005) illustrated that USG will lag 30 minutes behind plasma osmolality as a measure of current hydration status. Since only one indicator of hydration status was measured (USG), correlating USG with other indicators is not possible. However, each subject gave two urine samples, providing added internal reliability. The lag time in USG may partly explain the weaker than expected results between activity and USG as the hydration-related effects of activities would be delayed. However, since the potential lag would be the same for all participants, it is unlikely to have systematically biased the results.

Another limitation deals with the environmental data. While the urine measure is a point estimate that reflects the environmental, physical, and health conditions leading up to that time, the temperature data are point estimates at the time urine was collected. Nevertheless, the temperature at each period would be a close reflection of the temperature individuals were experiencing leading up to the urine samples. Wind speed and humidity were not assessed, which can change the real feel of temperature and aid or disrupt the ability to thermoregulate (Lundgren et al., 2013). The real feel of temperature was likely higher in the sun as temperature was recorded in the shade. It is important to note that weather does not equate to climate, and the associations reported here deal with temperature, which we can extrapolate using climate change models to try to understand how increased variability will affect hydration in the future.

Finally, while the Hausman test indicated that the RE models were better suited to this data than FE models and RE regression allows inferences to be made beyond the sample, RE models are also prone to omitted variable bias (Wooldridge, 2009). In this case, diet, which was not included in the model, may be contributing to the observed effect. Diet intake for the 24 hours leading up to the focal follow was not recorded and therefore could not be included in the models. Nevertheless, the variables included in the model accounted for up to 60% of the explained variance of USG, far above typical health models (Worthman & Kohrt, 2005).

Conclusion

The repercussions of dehydration or failing to meet individual water needs can be extreme. This is one of the first studies to quantitatively assess ambient temperature and lifestyle transitions in relation to USG among an indigenous Amazonian population. The association found between temperature and hydration status has significant implications for understanding how global climate change may influence daily water needs among populations undergoing lifestyle transitions and adaptation to hot, humid environments. If temperatures continue to increase, populations living in hot, humid environments will have higher water needs and suffer greater heat-related morbidity and be more vulnerable to dehydration if they fail to meet those needs (Lundgren et al., 2013). The implications of this research raise questions as to whether differences in subsistence activities, like productivity and hunting returns, can be explained by variation in hydration status or heat load between individuals (Tanner et al., 2013). More research is needed among native populations living in hot-humid environments linking chronic dehydration on performance and productivity to understand the health and economic implications of dehydration and climate change. Future research should expand on this study to see if individuals in different populations undergoing lifestyle transitions in different climates are also at high risk of dehydration.

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Table 4.1: Tsimane' adult sample characteristics and descriptive statistics

	Men (n=18) Mean ± SD (Range)	Women (n=18) Mean ± SD (Range)
Age, years	40.2 ± 17.3 (20-77)	37.2 ± 21.1 (14-80)
USG, g/ml	1.022 ± 0.008 (1.006-1.037)	1.018 ± 0.007 (1.003-1.034)*
Dehydrated, %	50%	33%
Diarrhea, %	5.5%	11%
Height, cm	162.7 ± 5.2 (150.2-170.4)	151.7 ± 4.5 (142.9-157.4)**
Weight, kg	60.2 ± 5.8 (48.6-68.9)	54.7 ± 8.6 (42.4-71.7)**
BMI, kg/m^2	22.7 ± 1.7 (19.0-25.4)	23.7 ± 2.8 (20.0-29.8)+
Body fat, %	15.2 ± 3.2 (10-22.6)	26.3 ± 6.9 (11.5-37.6)**
Total body water, %	61.4 ± 3.4 (53.3-68.4)	50.6 ± 4.6 (44.1-60.5)**
Temperature, °C	28.1 ± 4.9 (18.0-37.5)	27.3 ± 4.1 (17.0-35.0)
Activity Level:	1.5 ± .8 (1-3)	1.3 ± 0.6 (1-3)
Light, 1	69%	72%
Moderate, 2	11%	22%
Heavy, 3	20%	6%
Close Village	52.3%	47.7%
Distant Village	46.7%	53.3%

** $p<0.01$, * $p<0.05$, + $p<0.1$, using two-tailed t-test.

Table 4.2: Activity classification for focal follows and reported activities

Activity level	Examples of activities categorized from focal follows and self-reports
Light	Sitting, talking, breastfeeding, childcare, making palm-thatch roofing, making woven bags.
Moderate	Fetching water, cooking, preparing fire and food, walking, some hunting, fishing, making chicha, grinding maize/rice, playing soccer.
Heavy	Work in the slash and burn field with machete or shovel, clearing fields, planting, cutting trees, hoeing, long hikes, some hunting, fetching and carrying palm-thatch from the old growth forest.

Table 4.3: Change in hydration status between samples dehydrated (USG >1.020) in sample 1 and sample 2.

	Not dehydrated sample 2	Dehydrated Sample 2
Not dehydrated sample 1	18	3
Dehydrated sample 1	3	12

Table 4.4: Random-effects panel linear regression of effects of temperature and individual characteristics on urine specific gravity of Tsimane' adults.

	Urine Specific Gravity					
Variables	1	2	3	4	5	6
Temperature °C	0.00094** (0.0021)	0.00088** (0.0021)	0.00093** (0.00021)	0.00089** (0.00023)	0.0094** (0.00023)	0.00094** (0.00023)
Close village (Far village ref)	---	0.0036* (0.0018)	0.0036* (0.0017)	0.0036* (0.0018)	0.0037* (0.0018)	0.0035+ (0.0019)
Diarrhea (1=yes)	---	---	0.0058+ (0.0031)	0.0057+ (0.0032)	0.0064* (0.0032)	0.0066* (0.0033)
Weight (Kg)	---	---	---	---	---	-0.000081 (0.00019)
Height (m)	---	---	---	---	---	0.00017 (0.00027)
TBW (%)	---	---	---	---	-0.00034 (0.00024)	-0.00040 (0.00029)
Body Fat (%)	---	---	---	0.00014 (0.00017)	---	---
Activity Level:						
Light (reference)	---	---	---	---	---	---
Moderate	---	---	0.0030* (0.0015)	0.0031* (0.0015)	0.0037* (0.0016)	0.0036* (0.0016)
Heavy	---	---	0.0018 (0.0017)	0.0019 (0.0017)	0.0022 (0.0017)	0.0023 (0.0017)
Sex (1=male)	---	---	0.0031+ (0.0017)	0.0041 (0.0025)	0.0070* (0.0031)	0.0062 (0.0043)
Constant	0.993** (0.005)	0.996** (0.005)	0.99** (0.0055)	0.99** (0.0083)	1.008** (0.012)	0.99** (0.037)
Overall R^2	0.46	0.51	0.58	0.58	0.60	0.60
Observations	72	72	72	70	68	68
Subjects	36	36	36	36	35	35

Standard errors in parentheses; Models control for a set of time sampled dummy variables (n-1=3); Trad: traditional; TBW: % total body water; Observations vary because Tanita scale does not compute TBW for subjects younger than 18. ** p<0.01, * p<0.05, + p<0.1.

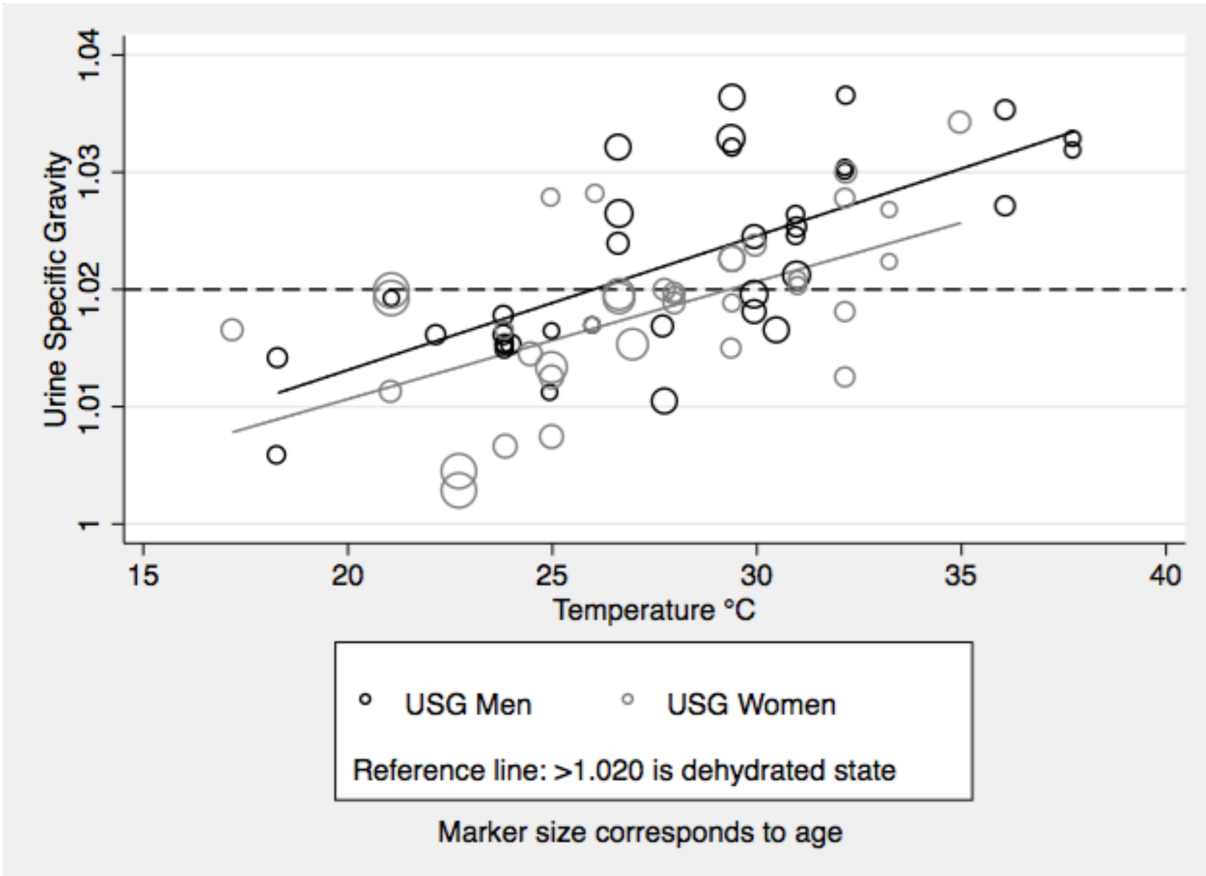

Figure 4.1. The relationship between urine specific gravity (USG) and temperature at time of sample by sex (both samples shown for each individual).

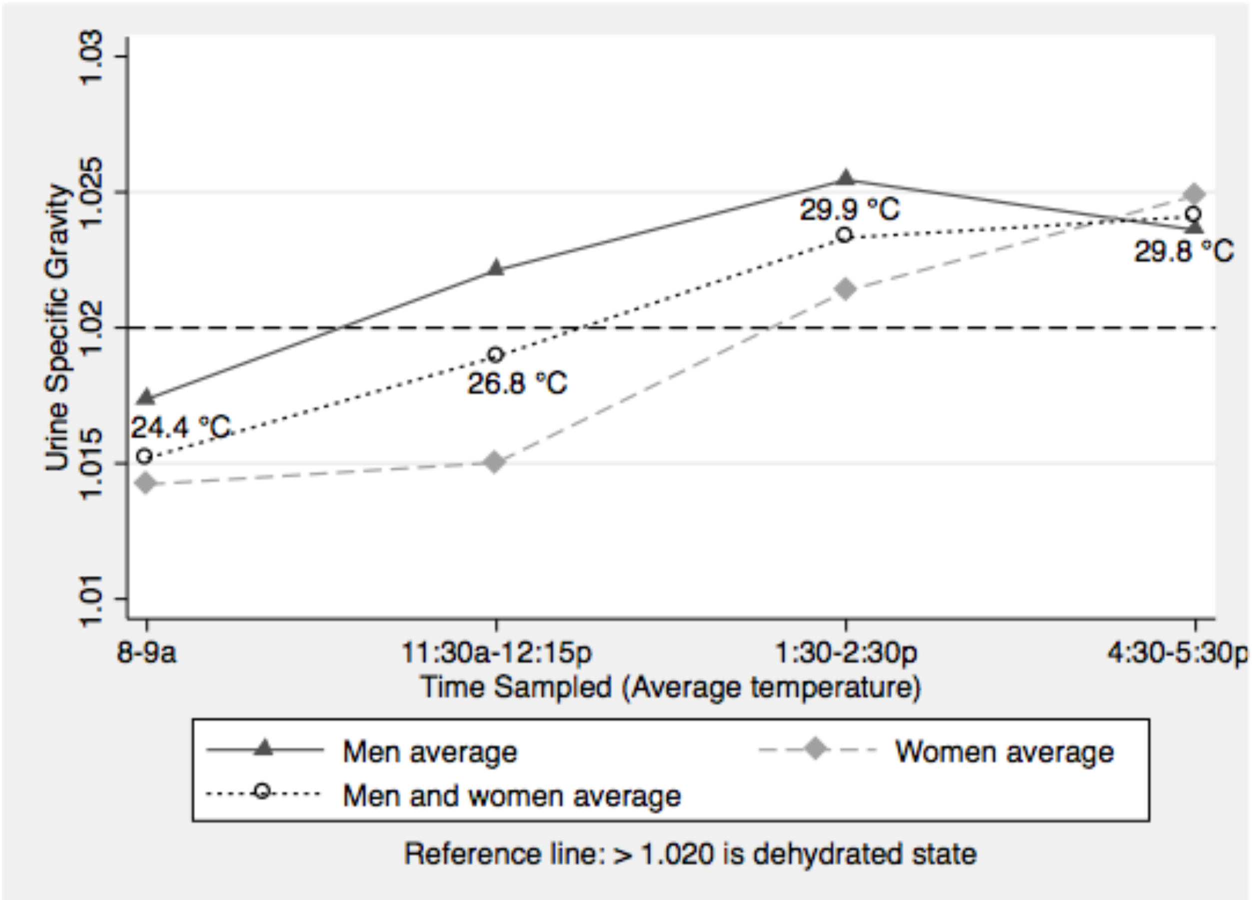

Figure 4.2: Average urine specific gravity and temperature by time period sampled for the sample and disaggregated by sex. Individuals were sampled in two of the four sampling periods, the morning or afternoon. The lines are connected to show sample average and continuity of the day rather than individual continuity.

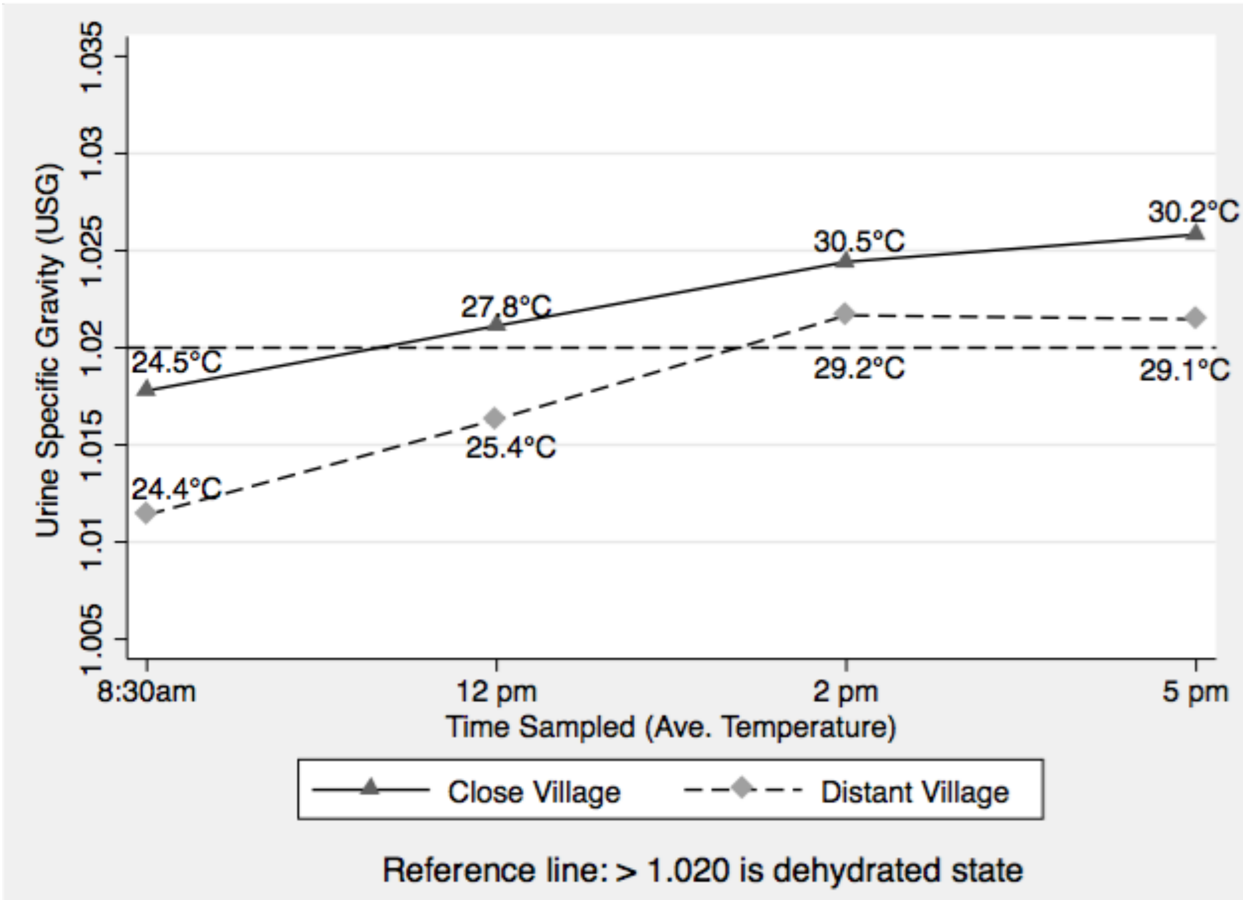

Figure 4.3: Average urine specific gravity and temperature by time period sampled for the sample and disaggregated by village.

CHAPTER 5

PREDICTORS AND HEALTH OUTCOMES OF WATER INSECURITY AFTER A FLOOD AMONG AN INDIGENOUS POPULATION IN THE BOLIVIAN AMAZON[3]

[3] Rosinger, A. To be submitted to *Social Science & Medicine*.

Abstract

While 748 million people worldwide do not have access to clean water, a large proportion of these populations also live in flood-prone regions. Floods increase the risk of diarrheal diseases and are expected to occur with increased frequency in the 21st century. Water insecurity is linked to emotional distress of populations living in water scarce regions or where access to clean water is limited, yet this concept has not been examined closely among populations living in flood-prone regions. This paper examines how differences in environment and lifestyle among Tsimane' forager-horticulturalists in the Bolivian Amazon are related to water insecurity before and after the major floods of 2014, and in turn, how water insecurity is associated with diarrhea and dehydration. Pre-flood data come from qualitative interviews conducted with 36 household heads, participant observation, and water quality analysis between September 2013-January 2014. The interviews were used to create a locally-adapted water insecurity questionnaire. Post-flood data were collected through a water insecurity survey alongside anthropometric, health exams, and urinalysis using near-exhaustive sampling in two villages, yielding a sample of 118 adults and 119 children (under 12 years of age) in 63 households between March-April 2014. Overall, 89% percent of adults reported medium or high levels of water insecurity and the flood likely increased water insecurity scores. Tobit regressions suggest that primary water source, age, and village membership predict water insecurity scores of adults. Multiple logistic regressions suggest that adults who reported high water insecurity were nine times more likely to have diarrhea than adults with low water insecurity (Odds Ratio 8.9; 95% CI: 0.75-109.7). Children whose mothers reported medium (OR: 6.6; 95% CI: 1.09-43.7) or high (OR: 5.4; 95% CI: 0.91-32.0) water insecurity scores had a higher probability of dehydration than children whose mothers reported low water insecurity. Increased frequency of flooding has the potential

to systematically increase multiple dimensions of water insecurity among populations living in flood-prone regions. This research suggests a measure of psychosocial stress related with water insecurity is associated with dehydration and disease occurrence.

Introduction

Currently, 748 million people worldwide lack access to improved drinking water sources (WHO and UNICEF, 2014). Many of these people experience water insecurity, which is defined as "insufficient and uncertain access to adequate water for an active and healthy lifestyle" (Hadley & Wutich, 2009; Stevenson et al., 2012). Water insecurity has three key dimensions: inadequate water supply, insufficient access to water distribution systems, and inadequate water for a healthy lifestyle (Stevenson et al., 2012). The construct of water insecurity is an experience-based measure that is reported by individuals who are dealing with scarcity of a critical resource (Hadley & Wutich, 2009). Water insecurity is important to understand because different levels of this insecurity may affect dietary and health behaviors regarding how humans interact with their environment to meet their water and sanitation needs that may be used to buffer stressors within an environment.

Two gaps exist in the water insecurity literature in comparison with the more established food insecurity literature. First, while evidence for nutritional and health outcomes of food insecurity have been well-established (Belachew et al., 2013; Hadley and Crooks, 2012; Hampshire et al., 2009), the physical health outcomes of water insecurity are largely undocumented, apart from recent linkages to mental health and well-being (Ennis-McMillan, 2001; Wutich & Ragsdale, 2008; Stevenson et al., 2012; Wutich & Brewis, 2014). Dehydration is underexplored as a potential health outcome of water insecurity; yet, it is the most proximate outcome associated with meeting water needs (Wutich and Brewis, 2014). Second, while natural disasters like droughts are often linked to food insecurity through scarcity and higher food prices (Hadley et al., 2012), water insecurity has not been examined among populations living in flood-prone regions. However, a large proportion of populations without access to clean water also live in flood-prone regions. Floods increase the risk of diarrheal diseases and are expected to occur with increased frequency in the 21st century (Magrin et al., 2014; Reynaud et al., 2013). The present paper attempts to fill these gaps and extend the construct of water insecurity by examining whether individuals who live in areas that have an abundance of dirty water in flood-prone regions experience water insecurity in similar ways to individuals living under water-scarce conditions. Second, it examines whether this measure is associated with differential risk of diarrhea and dehydration following a major flood in the Bolivian Amazon.

Water insecurity, flooding, and health

Water insecurity is an emerging topic as the number of articles published that mention a variant of this term have increased exponentially in both the physical and social sciences since 2000 (Cook and Bakker, 2012). Anthropologists have explored the domain of water insecurity among populations facing water issues in places as diverse as Alaska, Bolivia, Mexico, and Ethiopia (Eichelberger, 2010; Ennis-McMillan, 2001; Stevenson et al., 2012; Wutich and Ragsdale, 2008; Wutich & Brewis, 2014). In Mexico, Ennis-McMillan (2001) found that rural residents who lacked consistent access to water endured emotional distress, stating that the residents “suffered from water.” In Bolivia, Wutich and Ragsdale (2008) found that the cultural idioms of distress surrounding water insecurity were associated with anger, bother, fear, and worry and that there were differences in these emotional responses within the household (Wutich, 2009). Extending water insecurity to include social dimensions, Stevenson and colleagues (2012) found that women's water insecurity significantly predicted psychosocial distress, or symptoms of common mental disorders. Overall, these anthropological studies have laid important groundwork illustrating that water insecurity captures the mental toll of the daily struggle to meet a basic human need of drinking water and access to water for adequate sanitation (Gleick, 1996; Jepson, 2014).

The idea that water insecurity is associated with mental health outcomes is predicated on the epidemiological link between a lack of clean water and diarrheal diseases and dehydration (Black & Lanata, 2007; Arar 1998; van der Hoek et al 2001; van der Hoek et al 2002), such that people worry they will either get sick from their water or that they will not have enough water to drink or to cook and do household chores. However, the relationship between water insecurity and diarrhea and dehydration has not been tested directly.

Moreover, water insecurity has most commonly been examined among populations living in water-scarce environments. Yet living in a water-rich environment where the available water is unclean or in a flood-prone region can be equally stressful (Wutich et al., 2014). When access to clean water is limited and uncertain, research has indicated that an emotional toll hits individuals dealing with resource struggles similar to an illness as individuals "suffer from water" but also "suffer for water" (Ennis-McMillan, 2001; Yongsi, 2010; Sultana, 2011). This suffering can extend to water-rich environments without improved sources through worry that children will be chronically infected with parasites and bacteria leading to diarrheal and parasitic diseases.

The three dimensions of water insecurity - access, adequacy, and lifestyle – which are paramount for health, are easily disrupted by natural disasters, particularly floods. Research has shown that individuals are more likely to use sources they perceive to be clean whether the sources are clean or not (Nichter, 1985; Nagata et al., 2011; Jain et al., 2014). Perception of water is informed by a person's understanding of their local ecology (Gartin et al., 2011). However, shocks in the form of natural disasters often create uncertainty regarding aspects of water quality and cleanliness of water sources. Flooding events increase the uncertainty of the cleanliness or quality of water because rivers become more turbid and carry away trash and in severe cases humans and livestock (Few, 2013; Reynaud et al., 2013). Flooding serves as a shock to water systems as well as to perceptions of the water environment, which can produce long-lasting distrust of water sources (Nagata et al., 2011).

Indigenous populations in developing countries are often the most vulnerable to natural disasters because of socioeconomic disparities (Few, 2003; Khan et al., 2014). In particular, in regions without proper infrastructure, flooding places substantive stress on water systems and can disrupt many aspects of life and health (Ahern & Kovats, 2013). Even cleaner water sources, like tube wells, are vulnerable to water intrusion and contamination during floods (Luby et al., 2008). The risk of diarrheal diseases and other infectious diseases increase substantially following flooding events as reported in various locations, including Bangladesh, Vietnam, and Mumbai (Brouwer et al., 2007; Few, 2013; Reynaud et al., 2013; Subbaraman et al., 2013; Khan et al., 2014). Therefore, it is highly likely that flooding heightens perceptions of water insecurity.

The Bolivian Amazon is an ideal location to examine this problem because it is a hot-humid environment with high pathogen loads and has a heavy rainy season that can cause seasonal flooding (Benefice et al., 2007; Blackwell et al., 2011; Tanner et al., 2013). In this environment, people must consume large amounts of water (from liquids and foods) to avoid dehydration associated with thermoregulation but there is a scarcity of improved water sources (Rosinger & Tanner, 2015). Therefore, people may be closely attuned to the quality of water and aware of the consequences of drinking low quality water, including diarrheal disease. Additionally, clinical research suggests that diarrhea and failure to meet water needs (chronic dehydration) may lead to malabsorption, weight loss, cognitive deficits, headaches, economic productivity loss, and possibly death (Pelto & Pelto, 1989; Mendez & Adair, 1998; Hunter et al., 2009).

The goals of the present paper are threefold: 1) to examine how water insecurity differs in a water rich ecology from a water scarce ecology by using a recent flood to understand how an abundance of dirty water may affect the three dimensions of water insecurity; 2) to test the predictors of water insecurity of a native population living in the Amazon in a flood-prone region; and 3) to assess whether higher levels of water insecurity are associated with elevated risks of diarrhea and dehydration, both measures of well-being that result from a lack of access to clean water, among adults and children.

Study population and flood

Approximately 15,000 Tsimane' live in the lowland department of the Beni, Bolivia in ~100 villages along the banks and tributaries of the Maniqui River. The climate in the region presents high, stable average temperatures (26.8 °C average yearly temperature), high humidity, and high rainfall (1,743 mm mean rainfall) (Godoy et al., 2008). The year is split into two distinct seasons. The dry season lasts from May to October, while the wet season occurs from November to April. Lowland Bolivia, similar to most of Amazonia, has limited access to clean water (Rufener et al., 2010). Across Tsimane' villages, six raw, or untreated, water sources exist: river, streams, ponds, open wells and covered hand pump wells, and collected rainwater. The open and hand pump wells (hereafter hand pumps) are only available in Tsimane' villages that are close to the main market town of San Borja and are the result of public health interventions by non-governmental organizations, including Engineers Without Borders. These two water sources tap into ground water and are significantly cleaner than the surface sources (Rosinger & Tanner, 2015). Wells and hand pumps are also a source of community pride and are acknowledged to be cleaner, healthier, and preferable to surface sources provided they are not significantly farther than the river.

The health profile of Tsimane' is described in detail elsewhere (Tanner & Rosinger, 2014), but is characterized by high rates of infectious diseases, in the forms of intestinal parasitism (56-80%) and diarrhea (Gurven et al., 2007; Blackwell et al., 2011; Tanner et al., 2013). Previous research found that Tsimane' have flexible hydration strategies and get drinking water from a variety of environmental raw sources as well as from foods and fruits (Rosinger & Tanner, 2015). This research also found that the intake of a higher percentage of water from foods than from raw water or other liquids was associated with a lower risk of gastrointestinal illness.

During the course of the fieldwork for this study, exceptionally heavy rains between December 2013-February 2014 produced a historic flood in the southwestern Amazon basin of Peru, Bolivia, and Brazil. January and February of 2014 were the rainiest months since the beginning of observations in 1944 at three different sites in the Beni, Bolivia (Espinoza et al., 2014). A rain station in Rurrenabaque, which is a close town to the Tsimane' territory, recorded 1100 mm of rain in under three weeks, between January 24th and February 10th, which represents more than 63% of the average annual rainfall in the region (Godoy et al., 2008). The flood in the Beni, Bolivia was declared a national emergency by the Bolivian government on February 4th, 2014. The majority of Tsimane' villages had standing water for between seven and 28 days. The duration and severity of the flood produced large property and crop losses in their horticultural fields. Villages downriver from the central city of San Borja had standing water for longer periods than villages upriver from San Borja because they are at lower elevations. The flood largely subsided by the end of February upriver, but downriver, the flood changed the path and ecology of the Maniqui River, which resulted in shallower water that created additional flooding events following heavy rains. Standing water and mud remained throughout many of the downriver villages until mid April.

Methods

Research Design

Data come from an observational study conducted in two Tsimane' villages between September 2013 and April 2014. This period encompasses the 2014 flood described above. The study's original intension was to examine how lifestyle differences between the two communities related to water insecurity, and in turn, how water insecurity was associated with diarrheal prevalence and hydration levels in a water-rich environment without access to clean water, but the unprecedented flooding added an interesting dimension to the problem. The two research communities were selected to provide variation in distance to the main market town, market participation, and lifestyle. The close village to the main market town is an hour car ride to San Borja during the dry season or a 2-3 hour motorized canoe ride year round, and has access to river, stream, pond, hand pumps, and well sources. The distant village is a two-day motorized canoe ride away from the main market town of San Borja year-round and only has access to the river and stream for water.

Between September 2013 and January 2014, interviews and participant observation took place in both communities. A stratified, representative sample of 36 household heads (18 male) participated in an hour-long semi-structured interview on topics such as perceptions of water,

water quality, diarrhea, thirst, and hydration, which also yielded pre-flood data on anthropometrics, diarrheal prevalence, and hydration levels. During a second phase (March-April 2014), all households in both communities were invited to participate in a survey including the water insecurity questionnaire, health examination with a doctor (who was part of the research team), urinalysis, and anthropometric measurements. Both male and female household heads were asked the water insecurity questionnaire separately, yielding a total sample of 118 adults in 62 households. I also collected the same health information (health exams, urinalysis, and anthropometric measurements) for children 12 years and younger (n=119) in the households (See Table 5.1 for sample characteristics). Water samples from the primary water sources in both villages were collected to analyze for water quality post-flood and to test how water quality was associated with water insecurity. While it is not possible to assess the effect of the flood in conjunction with changes in water insecurity since water insecurity was not measured before the flood, inferences about changes in diarrheal and dehydration prevalence are possible for adults due to pre and post flood data.

Permission was granted by the Grand Tsimane' Council, community leaders, and each participant gave oral consent before data collection. The Institutional Review Board at the University of Georgia approved the study protocol (IRB #2012-10290-0).

Water Insecurity Scale Construction

Using the results of interviews and participant observation among Tsimane and using water and food insecurity studies as models (Melgar-Quinonez et al., 2006; Stevenson et al., 2012; Wutich and Ragsdale, 2008), I designed a locally-adapted nine question survey (See Table 5.2) during January 2014 addressing the three dimensions of water insecurity: access, adequacy, and lifestyle. The water insecurity questionnaire was designed before the flood, yet two of the questions (#4-5) were aimed at understanding how excessive amounts of water affect a dimension of water insecurity.

Each water insecurity question was asked in the following format: “In the last month, have you been hurt getting water by falling or another reason?” If the respondent stated “no” they received a 0 for that question and we proceeded to the following question. If the respondent stated “yes” then a follow-up question was asked: “rarely, sometimes, or always.” If the respondent stated “rarely,” they were given a 0, if they responded “sometimes” or “always,” they were given a 1. The minimum score was a 0 and the maximum score was a 9. I constructed a categorical variable from the continuous following Melgar-Quinonez and colleagues (2006) using the following cut off points: Low water insecurity: 0-3; Medium water insecurity: 4-6; High water insecurity: 7-9 (See Figure 5.1).

Water Sources and Water Quality Analysis

Water samples were collected following methods laid out by the United States Geological Survey (2006) from three sites (river, hand pump, and open well) in the close village and two sites (river and major stream) from the distant village (See Table 5.3). Two sets of samples were taken from each water source. The first sample of 500 ml was placed into a sterilized container and placed in an ice-filled cooler to be transported to the SEDES Beni environmental health laboratory in Trinidad, Bolivia to assess turbidity and other physical-chemical indicators of water quality. The second sample of 20 ml was added directly to a HACH PathoScreen field kit, which contained a powder-form dehydrated H_2S test reagent. This field kit allowed for in-field water quality analysis without the use of an incubator due to high ambient temperatures. The medium used by PathoScreen detects the presence of hydrogen sulfide-producing bacteria like Salmonella, Citrobacter, and others, and produces similar results to other field based tests

(Chuang et al., 2011). If the medium changed color from yellow to black or black precipitate formed within 24-48 hours, it was noted as positive for pathogenic bacteria.

Health Outcomes: Diarrhea

Health recall and a doctor examination were used to assess whether participants were suffering from diarrhea in the previous seven days (defined as 3+ instances of watery stool in 24 hours). Recall of illness is commonly used to assess health conditions (Schelling et al., 2005), and while recall periods beyond three days begin to underestimate true disease prevalence, the combination of health recall with a doctor exam helps to minimize this bias (Feikin et al., 2010). Previous research among Tsimane' indicates that parents often underestimate their children's health ailments (Aiello, 2013), so the doctor asked children directly about their health in the presence of their parents, and had their parents confirm or fill-in information.

Urine specific gravity and dehydration

I used urine specific gravity (USG), or the density of urine compared to the density of water, to measure hydration status. USG was analyzed using a digital handheld refractometer (Atago, Measurement accuracy ±0.001), which was calibrated daily with bottled water. USG is noted as the best indicator of hydration status for field measurements because of its non-invasive nature (Armstrong, 2007). USG ranges between 1.000 and 1.040 g/ml, and values above 1.020 are a cut-off point for clinical dehydration and represent approximately a 3% total body water loss (Casa et al., 2000).

Covariates

Age was measured by asking individuals their birthdate, how old they were, and verified with a government identity card or birth certificate when possible.

Ambient temperature was measured through an indoor/outdoor wall thermometer placed in the shade at the interview site (Springfield Precision #90116). Temperature was recorded at the time of the urine sample to the nearest 0.5° C.

The height of each individual was measured using a standing stadiometer, rounded to the nearest 0.1 cm (Seca 213), and weight was measured using a Tanita Bioimpedance scale (0.1 kg) following Lohman et al. (1988). BMI was calculated as kg/m^2.

Statistical analysis

Analysis was conducted in Stata 13.1 (College Station, TX). I used bivariate statistics including student's t-test and oneway anovas to assess trends in water insecurity and predictors and outcomes of water insecurity, setting α at 0.05. I also examined demographic and health trends pre and post flood in a subsample of adults. To assess the predictors of water insecurity, I used ordinary least squares tobit regression because the dependent variable of water insecurity is a continuous variable censored at both the low (0) and high (9) ends. Therefore, I set limits at those points to meet the assumptions of the model (Wooldridge, 2009). I use a village dummy variable to assess how village differences are associated with water insecurity and the health outcomes. To assess the most common health outcomes attributed to water insecurity (diarrhea and dehydration), I used multiple logistic regression to estimate models because both of the outcome variables are dichotomous.

For suitability of model selection, I used the Akaike Information Criteria (AIC) (Akaike 1974). The smaller the AIC, the better the model is suited to the data. I then modeled the adjusted predicted probabilities from the models to visualize effects over the primary independent variable of interest (Mitchell, 2012; Williams, 2012). In all regression models, I clustered robust standard errors by household to control for intra-household similarities and confounding between water insecurity and environmental and health variables of interest.

Results

Water Insecurity and water quality

Table 5.2 presents the results of the nine-item water insecurity scale (range 1-8). The Cronbach's alpha score, a measure of internal consistency, was low (0.53) suggesting heterogeneity of the index or that the nine questions in the index are not measuring just one latent underlying variable regarding water insecurity (Tavakol and Dennick, 2011). The questions aimed to capture access (#2, 6, 7), adequacy (#3, 8, 9), and lifestyle (#1, 4, 5) are different dimensions of water insecurity and may be capturing slightly different latent constructs. Principal components analysis confirmed that this index was multidimensional with 3 factors holding eigenvalues above 1.15. The factor loadings (in parentheses) matched onto the three dimensions relatively well and some questions touched on multiple factors. Factor 1 matched onto the dimension of adequacy as it was strongly correlated with questions 3 (0.63), 5 (0.52), 8 (0.73), and 9 (0.74); factor 2 was most correlated with the dimension of access and questions 2 (0.41), 6 (0.40), and 7 (0.45); and factor 3 was associated with the dimension of lifestyle and questions 1 (0.58), 4 (0.40), and 8 (0.54). The multidimensionality of this index likely means that alpha is largely underestimated (Sijtsma, 2009), but the implications will be further discussed in the limitations section of the discussion below. Figure 5.1 shows the proportion of adults reporting low, medium, and high water insecurity by village. The majority of adults in the two villages reported medium or high water insecurity, with only 11% reporting low water insecurity (Table 5.3).

Water quality analysis in both villages suggests that the river is contaminated with pathogenic bacteria (Table 5.4). In the close village, the river was highly contaminated with pathogenic *E. coli* and had a high turbidity of 148 NTU, whereas the well and hand-pump were both negative for pathogenic bacteria and had relatively low turbidity. In the distant village, both the river and a tributary of the river were positive for pathogenic *E. coli* and had higher turbidity readings, likely because of a recent rain event that occurred briefly before the sample was collected.

Dimensions of water insecurity affected by flooding

While the flood could have affected responses to many of the water insecurity questions, questions 4 and 5 were specifically designed to reflect stresses associated with too much water and rain. Post flood, 85% and 97% of the adults stated their houses had flooded and that their crops had died due to too much rain, respectively. While a normal rainy season may bring heavy rains that create muddy conditions in the households, houses are built on raised earth to avoid water coming into the house and widespread crop losses do not normally occur. Some crop losses are not unusual, though seasonal flooding increases crop failures (Gurven et al., 2012). For example, a 1992-1993 flood led to a 30.6% loss of rice harvest by households in 19 Tsimane' villages (Godoy et al., 1998). In a non-severe seasonal flooding year, 2005-2006, median crop losses were 0.03 hectares (ha) of rice, 0.03 ha of plantains, 0.02 ha of corn, and 0.02 ha of manioc out of a median 1.63 ha of horticultural fields (Gurven et al., 2012). Plantains and manioc are the most vulnerable crops to flooding. Therefore, while a normal rainy season may create slight crop losses and increase a small percentage of individuals' water insecurity, this historic flood likely increased almost every participant's water insecurity score by 1-2 points on the 9-point scale more than during the dry season.

As stated earlier, the flood affected the two villages in different severities. It is highly likely that the flood affected the water quality of all raw water sources in both villages. During the flood, many dogs and livestock were swept away, meaning that the water was contaminated with feces and dead animals. Fifty-nine percent of adults indicated that in the last month they changed water sources because of the water quality, many directly discussing the flood as the precipitating reason for their action.

During the survey, additional open-ended interview questions were asked to 39 of 118 (33%) participants regarding how the flood affected their water sources and their decisions to use different water sources after answering the water insecurity survey. A 23 year-old single mother who lives in the close village four minutes walking from a hand-pump, stated that she did not switch water sources in the last month but that the water from the flood covered the pump base, which had cracks and the water coming out of the pump was turbid. Her mother, who lives in the same household, stated that during the flood they had to pump and dump water from the hand-pump for an hour for the water to be clear again due to river water intrusion. Another adult stated, “We built our new house to be close to the well,” but during the flood his family retreated to their second house deeper in the forest, where they have access to a hand-pump, which was not affected by the flood because it was on higher ground.

Some families when asked if they changed water sources during the flood stated that they had not despite the deterioration in quality citing no other water sources nearby and that they do not have enough buckets to collect rainwater reliably. An old couple who only have access to the river stated “when [the river] is very dirty, we can’t drink at all and we have even more thirst.” One cluster of families had a hand-pump installed in the early 2000s but no longer use it because of a lack of maintenance. One of the adult males who lives beside it stated, “We have a pump, but the water is dirty, so we don't use it. We use the river instead." The disrepair on the hand-pump reduced the options for water sources.

Health profiles of adults also changed before and after the flood, though not dramatically (table 5.1). When examining the change in diarrheal and dehydration prevalence in a subsample of adults measured pre and post flood, there were significant increases as pre-flood prevalence of diarrhea in both villages combined was 8%, which increased to 19% post flood; while dehydration prevalence was 42% pre-flood and increased to 61% post-flood (two-tailed t-test $p<0.05$).

Predictors of water insecurity

Of the nine water insecurity questions, only question 1 presented significant differences between sexes as 24% of women to only 7% of men answered they had been injured in the past month getting water (two-tailed t-test $F=2.7$, $p=0.008$).

Three of the water insecurity questions as well as the overall water insecurity score were significantly different based on the primary water sources used by participants. The proportion of individuals who answered in the affirmative to questions 3 (anova $F=2.86$; $p=0.027$), 7 (anova $F=14.2$; $p=0.000$), and 8 (anova $F=2.73$; $p=0.033$), which address aspects of adequacy of water quality, concern regarding health associated with water, and lifestyle was lowest among those who used the hand-pumps and highest among those who used the stream. Overall water insecurity score was lowest among people using the hand-pumps (4.7, n=21), whereas individuals using the well (5.5, n=16), river (5.9, n=56), stream (5.9, n=16), and pond (6, n=9) as primary sources reported higher water insecurity ($F=2.76$; $p=0.03$).

Four of the water insecurity questions varied significantly by village. Adults from the close village answered questions 5 (100% vs 90%, anova $F=9.16$; $p=0.003$), 8 (87% vs 48%, anova F=23.2; p=0.000), and 9 (90% vs 71%, anova F=6.4; p=0.013) with a higher percentage than the distant village. Adults from the distant village answered question 7 with a higher percentage (84% vs 51%, anova F=11.33; p=0.001). However, overall score, while higher among individuals in the close village was not significant in bivariate analyses (t-test=0.50; p=0.61).

Finally, age was negatively associated with the overall water insecurity category with the average age of 41.6 years in the low water insecurity category, 35.8 years in the medium category, and 29.1 years in the high category (anova F=2.71, p=0.07).

Health outcomes of water insecurity

The overall water insecurity score was higher for adults who reported diarrhea (6.3) than those who did not (5.5) in the previous week (t=2.2; p=0.03). Using oneway anova, prevalence of diarrhea was significantly different by WI category (F= 4.24; p= 0.017). Adults from low water insecurity households had a 7.6% prevalence of diarrhea in the past week, whereas adults from medium water insecurity HHs had 13.5% diarrhea prevalence and adults from high water insecurity households had 35% prevalence. The overall effect of water insecurity category on prevalence of diarrhea was significant using the post-estimation command (chi2= 6.91, p=0.032.). The water insecurity level of both parents was not associated with the risk of diarrhea for children. High water insecurity was not associated with risk of dehydration for adults, but maternal water insecurity was associated with the risk of dehydration for their children (oneway anova F=3.34; P=0.04).

Regression Analysis

Table 5.5 presents the tobit regression results assessing the predictors of water insecurity for adults. As expected, people who used the hand pumps as their primary water source reported significantly lower water insecurity compared to those using the river (Model 1; β = -1.16; P =

0.001). The results are stronger when this relationship controls for sex, community membership, and age (model 2; β = -1.31; p=0.000). The results for model 2 are illustrated in Figure 5.2 as the adjusted water insecurity score for adults using the hand-pump was 4.6 vs. 6.0 for adults using the river. In model 2, adjusting for water source, age was inversely significantly associated as younger individuals had higher water insecurity. Additionally, adults living in the distant village had lower water insecurity than adults living in the close village with the association approaching statistical significance (p=0.07).

Table 5.6 reports the results for the logistic regression estimating the relationship between water insecurity category and risk of diarrhea and dehydration for adults. Models 1 and 2 illustrate that adults who reported high water insecurity were 6.6 to 8.9 times more likely to experience diarrhea in the past week than individuals who reported low water insecurity. While these results approached statistical significance (p = 0.09), the effect sizes are large indicating that the relationship is practically significant. Figure 5.3 illustrates the predicted probabilities of diarrhea adjusting for the covariates in model 2, and shows that the probability of diarrhea for adults with low water insecurity was only 6% and that this increased to 37% among adults with high water insecurity. Models 3 and 4 in Table 5.6 suggest that water insecurity category is not significantly associated with risk of dehydration for adults. While the odds ratios are above one for both medium and high water insecurity, indicating an elevated risk, this relationship is not significant and the only two predictors of dehydration are community membership and ambient temperature.

Table 5.7 reports the results for the logistic regression estimating the relationship between the mother's water insecurity level and risk of diarrhea and dehydration for her children. Models 1 and 2 show that unlike for adults, maternal water insecurity level was not associated with risk of diarrhea for their children. Conversely, maternal water insecurity category was strongly related to risk of dehydration for children (models 3-4). Adjusting for confounders, the results weaken slightly as children whose mothers reported medium or high water insecurity had 6.9 (p=0.04) and 5.4 (p=0.06) higher odds of being dehydrated, respectively (Model 4). Figure 5.4 illustrates the predicted probabilities of dehydration for children based on model 4 and shows that the probability of dehydration is only 11% for children whose mothers report low water insecurity, whereas children with mothers who reported medium or high water insecurity have a probability of 46% and 40% for dehydration, respectively.

Discussion

Individuals who live in flood-prone regions may also experience psycho-social stress related to water in ways similar to individuals who live in water scarce conditions. This discussion is organized around four main topics. First, I will discuss the implications of floods for dimensions of water insecurity. Second, I will discuss possible reasons behind predictors of water insecurity. Third, I will discuss potential pathways through which water insecurity may lead to higher risk of diarrhea and dehydration. Finally, I will discuss limitations of this study.

Floods and water insecurity

While water insecurity is generally discussed among populations living in water scarce regions (Stevenson et al., 2012; Wutich & Ragsdale, 2008), populations living in flood-prone regions are also at risk for experiencing the three dimensions of water insecurity (Brouwer et al., 2007; Reynaud et al., 2013). In South America, flooding is expected to occur more regularly throughout the 21st century (Magrin et al., 2014). Floods increase the possibility of injury getting water due to dangerous conditions. In the survey, women were significantly more likely to report injury in the last month than men. During the pre-flood qualitative interviews, Tsimane' women frequently complained about experiences with muddy riverbanks after heavy rains that led to falls and injuries and would show scars or tell stories of broken bones that occurred during bad falls in the past. Similarly, Sorensen et al. (2011) found that women in low-income countries are more likely to suffer injuries as well as have chronic pains from fetching water. The IPCC projects increased variability in rainfall with more precipitation during shorter intervals in the 21st century for the Amazon (Magrin et al., 2014). This change in weather patterns will likely increase dangerous conditions along riverbanks. The implications of these findings fall along Alston's (2013) claims that women, who are primarily responsible for the domain of water in Tsimane' life, are unevenly affected by global climate change disasters.

Flooding is also associated with worse water quality, increased risk of water contamination, and higher risk of diarrheal diseases (Brouwer et al., 2007; Luby et al., 2008). Despite the seeming abundance of fresh water in the South American Amazon, millions of people do not have safe drinking water or clean sanitation that results in stressed living conditions and malnutrition (Wolf, 2007). In these regions where potable water is not available, the biggest health risks are associated with consuming fecal-contaminated water (Carr and Neary 2008). In the present study, adults acknowledged the deteriorated water quality in the available water sources and the majority switched sources if they perceived a cleaner source was available. However, the switching of water sources seemed to be a general coping mechanism to the perception of dirty water and not simply the result of the flood as this adaptive response was frequently discussed in the pre-flood qualitative interviews. Nevertheless, not all adults in the close village and none of the individuals in the distant village had access to hand pumps and wells. The water quality analysis occurred about a month after the flood in the close village and as such may have not captured the immediate flood effects of water quality on the hand pump and well sources as individuals stated they pumped and dumped the water from those sources for the water to become clear again before the author arrived. Finally, the flood's effect on food availability, captured by crop losses in question #5, illustrates the strong connection between water and food insecurity highlighted by Wutich and Brewis (2014).

Predictors of water insecurity

Available water sources, village membership, and age predicted water insecurity for adults. These three factors may be working in concert to shape perception of the water environment. Individuals using hand pumps, the cleanest source, had the lowest water insecurity. This result was unsurprising because during qualitative interviews in September and October, Tsimane' listed this as the source they perceived to be cleanest (Rosinger & Tanner, 2015). Additionally, perception of water source cleanliness is directly linked to usage of water sources (Jain et al., 2014).

However, a potential underlying and unmeasured pathway driving these three predictors of water insecurity may be health education. Public health interventions tap into perceptual cues to drive health education about water and sanitation and can thereby perpetuate beliefs about water cleanliness (Curtis et al., 2009; De Ver Dye et al., 2011). Previous public health interventions may have increased awareness among Tsimane' that surface water sources are dirty, particularly in the close village. In the school of the close village, a USAID public health poster hangs on the wall that discusses three water purification techniques, including boiling, chlorine drops, and solaris (or sun uv radiation). Health messages regarding water cleanliness and sanitation are often delivered at schools (Greene et al., 2012). These health messages may be reaching younger adults particularly from the close village, both through the school, as they are the ones who saw the poster most recently, as well as through their experiences in the market as they are more likely to go into San Borja and be exposed there to health messages.

This potential finding suggests that in the close village, health education may be creating a perception that the available surface water sources are dirty and young adults are more attune to their water quality and as a result have higher water insecurity scores. An analogy to this unintended consequence of public health messages leading to potentially higher psychosocial stress about the environment is agricultural de-skilling described by Stone (2002). This phenomenon occurs when genetically modified crops are given to smallholders and they lose information and skill as a result. While water insecurity does not result in loss of skills, it can lead to increased stress, a sense of "loss of control," or hopelessness if the health information does not also provide the means to clean water (Few, 2013; Kuznetsov et al., 2013). However, an alternative explanation is that older adults built their houses in the most favorable locations close to the hand pumps and wells and that younger adults as a result build their houses slightly farther away and in less desirable locations. While this may be likely, young Tsimane' build their houses close to parents and kin, creating a cluster of houses often with a shared patio and fire. Therefore, when a young adult marries and builds a new house, their access to water sources does not change unless they decide to relocate entirely.

Health outcomes of water insecurity

In the present study, high water insecurity for adults predicts a nine-fold higher probability of diarrhea, while medium and high maternal water insecurity predicts a six-fold higher probability of dehydration for their children. It is unsurprising that high water insecurity was associated with probability of diarrhea for adults as the link between lack of access to clean water (a key dimension of water insecurity) and risk of diarrheal diseases has been clearly documented (WHO & UNICEF, 2014; Wutich & Brewis, 2014). For example, diarrheal diseases were highly common among Alaskan natives when water scarcity was an issue, which led to the installation of safe water access points and village sanitation in the 1950s and subsequent drops in diarrheal prevalence (Eichelberger, 2010). The intriguing implications of the present results are that while water insecurity is normally associated with mental health outcomes, like worry and stress, these perceptions map onto health realities. However, the results could also be explained by higher risk of diarrhea for adults as a result of the rainy season and flooding. Diarrheal epidemics following natural disasters like floods and tsunamis have been well-documented, and occur largely because of overcrowding, population displacement, changing of water sources, and deteriorated water quality (Brouwer et al., 2007; Watson et al. 2007; Luby et al., 2008; Khan et al., 2014).

The relationship between maternal water insecurity and children's probability of dehydration raises important questions regarding what is causing this relationship. A similar physiological relationship has been reported in the food insecurity literature where household food insecurity is associated with children's nutritional status (higher odds of stunting and wasting) particularly in lower income countries (Hadley & Crooks, 2012). Previous research shows that perceptions of water affect drinking behaviors (Nagata et al., 2011; Nichter, 1988; Jain et al., 2014). Moreover, previous research among Tsimane' shows that they rely on foods to make up half of their daily water intake (Rosinger & Tanner, 2015). Some Tsimane' reported that overly dirty and turbid water makes water virtually undrinkable and they would rather restrict intake and find alternatives to meet water needs than consuming it. This belief suggests they may take steps to buffer themselves and their children in an effort to reduce probability of getting sick from water. If the river water is incredibly turbid, they may not bring as much water back to the household and as a result may subtly withhold water from their children, as the availability in the household is lower. This action would protect them from diarrhea yet increase the child's risk of dehydration.

Limitations

This study is subject to two main limitations. First, Cronbach's alpha (α), which is a measure of internal consistency, is low (0.53) (Cronbach, 1951). Generally, α scores of 0.7-0.9 are recommended (Nunnally and Bernstein, 1994) for scales to be deemed reliable. Low α are normally "due to low number of questions, poor interrelatedness between items or heterogeneous constructs" (Tavakol and Dennick, 2011). A combination of these factors likely contributed to the low α. First, the length of questionnaires can artificially inflate or deflate the α, such that α grows as the number of items in the questionnaire grows (Nunnally and Bernstein, 1994; Sijtsma, 2009). Second, α represents the proportion of variance explained by the general or group factor of water insecurity rather than each item specific dimension (Cronbach, 1951).

Sijtsma (2009) illustrated the limited usefulness of α and that "there is no clear and unambiguous relationship between alpha and the internal structure of a test" and stated that unidimensionality has nothing to do with reliability. The aim of attempting to capture all three dimensions, or specific factors, of water insecurity in a locally meaningful way to Tsimane' designed through qualitative interviews, informant interviews, participant observation, and other indexes may also explain why the α is low. Principal components analysis confirmed that three primary factors underlie the index, which matched the three dimensions of water insecurity relatively well. Additionally, the fact that primary water source was significantly associated with overall water insecurity score adds credence that the questionnaire is measuring what it is supposed to be measuring. As a result, the water insecurity survey does appear to be testing the dimensions of water insecurity in this context and α is likely underestimating the reliability of this test (Tavakol and Dennick, 2011).

Second, the relationship between water insecurity and diarrhea and dehydration should be viewed as associations since data comes from a cross-sectional observational study in one season. While Wutich and Ragsdale (2008) showed that emotional distress from water insecurity did not differ significantly by season, in a water-rich context where flooding can dramatically change conditions, it is likely that collecting the data at the end of the rainy season resulted in overall higher water insecurity scores. Additionally, questions dealing with water quality and worry about sickness relating to water (questions from the adequacy dimension) may be more salient to adults when they or their children are suffering from diarrhea (Nichter 2008). This dimension may be driving the relationship for adults between water insecurity and diarrheal prevalence.

Conclusion

Increased frequency of flooding has the potential to systematically increase multiple dimensions of water insecurity among populations living in flood-prone regions. The theoretical implications of these findings suggest that individuals living in water-rich environments without access to clean water may also be "suffering from water" (Ennis-McMillan, 2001). This finding has implications for millions of individuals who live in flood-prone regions as they may be experiencing similar psycho-social stress to individuals living in water-scarce conditions, associated with the three dimensions of water insecurity (Stevenson et al., 2012).

This study also extends the connection between an experience-based measure of water insecurity with health outcomes associated with a lack of access to clean water (Wutich & Brewis, 2014). While the results are mixed, the findings indicated that perception of water insecurity may be used as a proxy for risk of diarrhea for adults and risk of dehydration for children. While perception of water insecurity may be more acute when an individual or their children are suffering from diarrhea and dehydration, the link between the two suggests that water insecurity in this context captures a key perceptual connection between the water environment and health outcomes.

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Table 5.1: Pre- and post-flood demographic characteristics of adult Tsimane' and post-flood sample characteristics of children, by village

	Pre-Flood		Post-flood	
Adults	Close Village (n 21) Mean ± SD (Range)	Distant Village (n 15) Mean ± SD (Range)	Close Village (n 87) Mean ± SD (Range)	Distant Village (n 31) Mean ± SD (Range)
Age (years)	37.1 ± 18.2 (17-80)	40.9 ± 20.6 (14-80)	34.2 ± 17.5 (15-85)	35.9 ± 19.1 (13-81)
Sex (1=male)	52.3%	46.6%	49.4%	54.8%
BMI (kg/m^2)	23.3 ± 2.6 (19.0-29.8)	23.2 ± 2.1 (19.3-27.1)	24.2 ± 3.2 (19.2-35.3)	22.9 ± 1.6* (19.9-25.3)
USG (g/ml)	1.022 ± 0.008 (1.006-1.037)	1.018 ± 0.006** (1.003-1.028)	1.022 ± 0.006 (1.005-1.034)	1.017 ± 0.007** (1.004-1.033)
Dehydrated (%)	47.6%	33.3%	72.1%	29.0%**
Diarrhea (%)	9.5%	6.7%	18.4%	19.4%
Temperature (°C)	28.2 ± 5.4 (17-37.5)	27.0 ± 2.8 (22.5-31)	27.9 ± 2.3 (22-31.5)	28.5 ± 2.5 (24-35)
Water Insecurity	---	---	5.7 ± 1.8 (1-9)	5.5 ± 3.0 (1-8)

	Post-Flood	
Children (12 years and younger)	Close Village (n 90) Mean ± SD (Range)	Distant Village (n 29) Mean ± SD (Range)
Age (years)	6.2 ± 3.0 (2-12)	6.8 ± 3.3 (2-12)
Sex (1=male)	58.9%	44.8%
BMI (kg/m^2)	16.3 ± 1.3 (14.4 – 21.5)	17.2 ± 1.6 (15.0 – 22.6)**
USG (g/ml)	1.018 ± 0.007 (1.004-1.031)	1.014 ± 0.006 (1.004-1.027)**
Dehydrated (%)	48.2%	22.2%*
Diarrhea (%)	42.2%	24.1%+
Temperature (°C)	28.2 ± 1.8 (24-31.5)	29.1 ± 1.8 (23-31)*
Maternal Water Insecurity	6.1 ± 1.8 (3-9)	4.4 ± 2.6 (1-8)**

** p<0.01, * p<0.05, + p<0.; 2 way t-test for differences between villages.

Table 5.2: Water Insecurity Index and overall response rate for a sample of Tsimane' adults

Water Insecurity Question	Yes
1) (In the last month,) have you been hurt fetching water by falling or another reason?	15%
2) Have you been thirsty because there wasn't enough water to drink in your house?	43%
3) Have you been worried about the quality of your water?	86%
4) Has your house flooded because of too much rain?	85%
5) Have some of your crops died because of too much rain?	97%
6) Have you been unable to get enough water to make chicha (local traditional beverage)?	15%
7) Have you changed water sources from your primary source because that water was dirty?	59%
8) Have you or someone else in your family been sick because your water was dirty?	77%
9) Have you been worried that your children would get sick because your water was dirty?	85%

Table 5.3: Water insecurity of a sample of Tsimane' adults from two villages

Water Insecurity	Close Village	Distant Village
Low (0-3)	8 (9%)	5 (16%)
Medium (4-6)	57 (66%)	17 (55%)
High (7-9)	22 (25%)	9 (29%)

Table 5.4: Available water sources and water quality analysis for two Tsimane' villages

Village	Water Source	No. (%) using source	Turbidity (NTU)	PH	Total Diss. Solids (ppm)	Iron (mg/L)	Pathogenic Bacteria
Close Village	River	76 (40%)	143	7.2	56.1	3.3	Pos
	Stream	7 (3.7%)	--	--	--	--	--
	Well	38 (20%)	4	7.3	145.7	0.3	Neg
	Pump	50 (26.3%)	38	7.6	119.8	3.1	Neg
	Pond	19 (10%)	--	--	--	--	--
Distant Village	River	52 (70.3%)	160	8.8	39.3	2.3	Pos
	Stream	22 (29.7%)	250	8.8	40.2	3.3	Pos

No.: Number; NTU: Nephelometric turbidity units; Diss.: Dissolved; ppm: parts per million.

Table 5.5: Tobit regression assessing predictors of water insecurity for a sample of Tsimane' adults from two villages

	Water Insecurity			
	1		2	
Independent Variables[a]	Beta	SE	Beta	SE
Water Source[b]: River (ref)	---		---	
Stream	0.06	0.69	0.39	0.57
Well	-0.38	0.57	-0.76	0.69
Pump	-1.16**	0.33	-1.31**	0.31
Pond	0.13	0.47	0.02	0.42
Sex (male=1)	---		0.01	0.21
Age (years)	---		-0.02**	0.01
Village: Close (ref)	---		---	
Distant	---		-0.71+	(0.38)
n (AIC[c])	118 (433.2)		118 (426.2)	

[a]Robust standard errors clustered by 62 households. [b]Water Source is a set of dummy variables. Constant not shown. [c]AIC, Akaike information criteria. ** $p<0.01$, * $p<0.05$, + $p<0.1$.

Table 5.6: Logistic regression of water insecurity on odds of adult diarrhea and dehydration for a sample of Tsimane' adults from two villages

	Diarrhea				Dehydration			
	1		2		3		4	
Independent Variables[a]	OR[b]	95% CI[c]	OR[b]	95% CI[c]	OR[b]	95% CI[c]	OR[b]	95% CI
Water Insecurity[d]: Low (ref)	1		1		1		1	
Medium	1.88	0.19-18.1	2.20	0.21-23.3	1.99	0.59-6.74	1.88	0.48-7.32
High	6.6+	0.70-62.7	8.91+	0.75-105.9	1.85	0.53-6.50	1.67	0.36-7.82
Sex	---		0.77	0.35-1.67	---		0.60	0.27-1.35
Age	---		1.02	0.99-1.04	---		1.00	0.97-1.02
Village: Close (ref)	---		1		---		1	
Distant	---		1.03	0.30-3.6	---		0.10**	0.03-0.32
Temperature (°C)	---		---		---		1.32**	1.07-1.64
BMI	---		---		---		0.88	0.74-1.05
n (AIC[e])	118 (112.0)		118 (116.3)		117 (161.5)		117 (142.5)	

[a]Robust standard errors clustered by household. [b]Odds ratio. [c]95% confidence interval. [d]Water Insecurity is a set of dummy variables. [e]AIC, Akaike information criteria. ** p<0.01, * p<0.05, + p<0.1

Table 5.7: Logistic regression of maternal water insecurity on odds of their children having diarrhea and being dehydrated for a sample of Tsimane' children from two villages

	Diarrhea				Dehydrated			
	1		2		3		4	
Independent Variables[a]	OR[b]	95% CI[c]	OR[b]	95% CI[c]	OR[b]	95% CI[c]	OR[b]	95% CI[c]
Water Insecurity[d]:								
Low (ref)	1		1		1		1	
Medium	1.20	0.36-3.93	0.61	0.17-2.18	10.0**	3.73-26.9	6.9*	1.09-43.7
High	2.00	0.62-6.44	1.03	0.27-3.97	8.1**	2.59-25.4	5.4+	0.91-32.0
Sex	---		1.09	0.41-2.90	---	---	0.99	0.40-2.47
Age	---		0.82**	0.71-0.95	---	---	1.01	0.87-1.18
Village: Close (ref)	---		1		---	---	1	
Distant	---		0.43	0.14-1.33	---	---	0.36	0.06-2.32
Temperature (°C)	---		---		---	---	1.35*	1.03-1.77
n (AIC)	119 (162.0)		119 (156.3)		110 (147.8)		110 (147.2)	

[a]Robust standard errors clustered by household [b]Odds ratio. [c]95% confidence interval. [d]Water Insecurity is a set of dummy variables. ** p<0.01, * p<0.05, + p<0.1

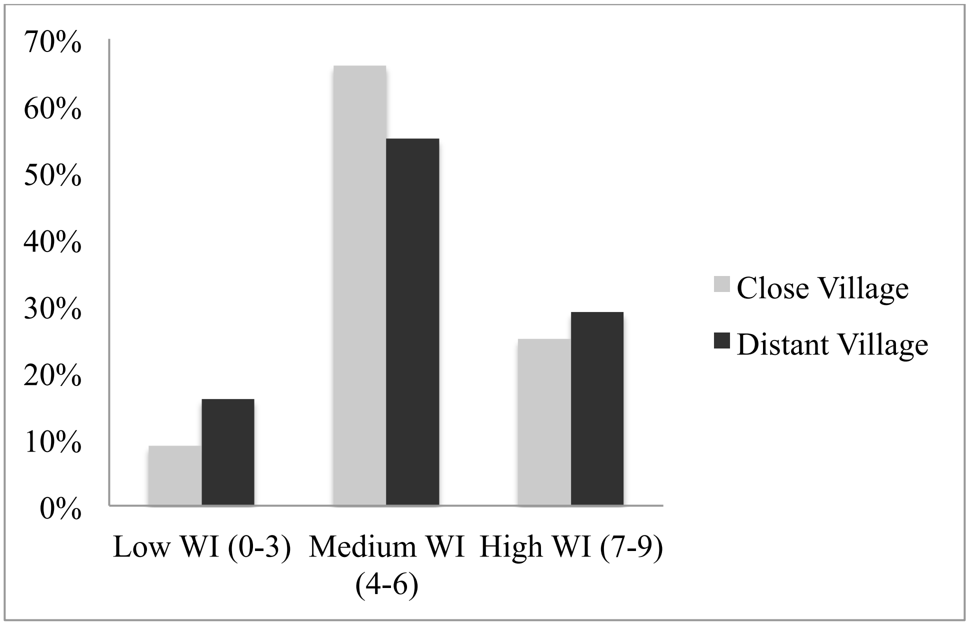

Figure 5.1: Water insecurity categories by village membership

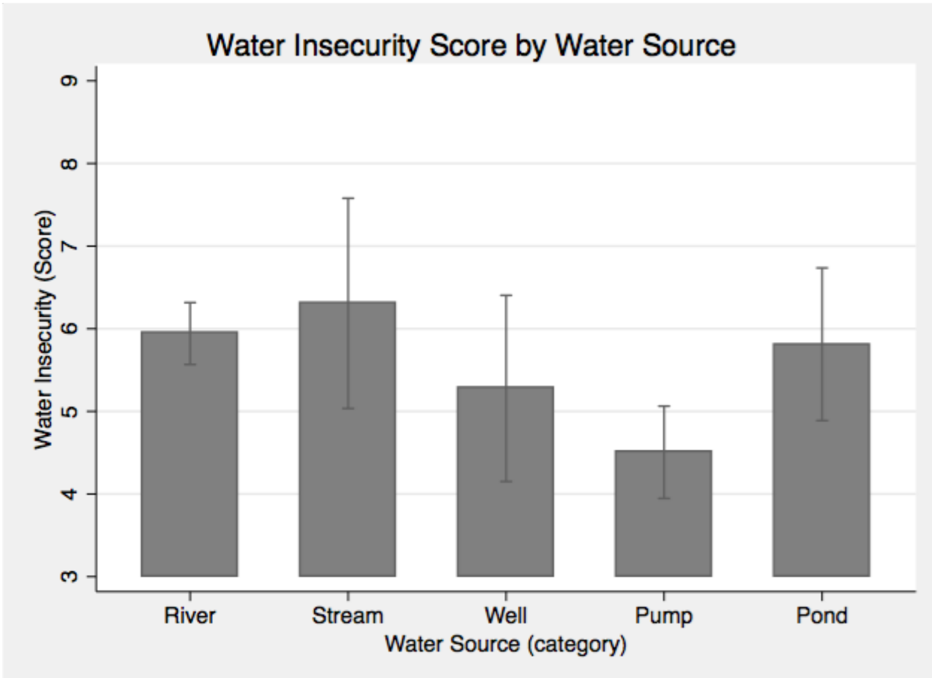

Figure 5.2: Margins plot of predicted adult water insecurity score by water source adjusted for covariates in table 5.5 model 2.

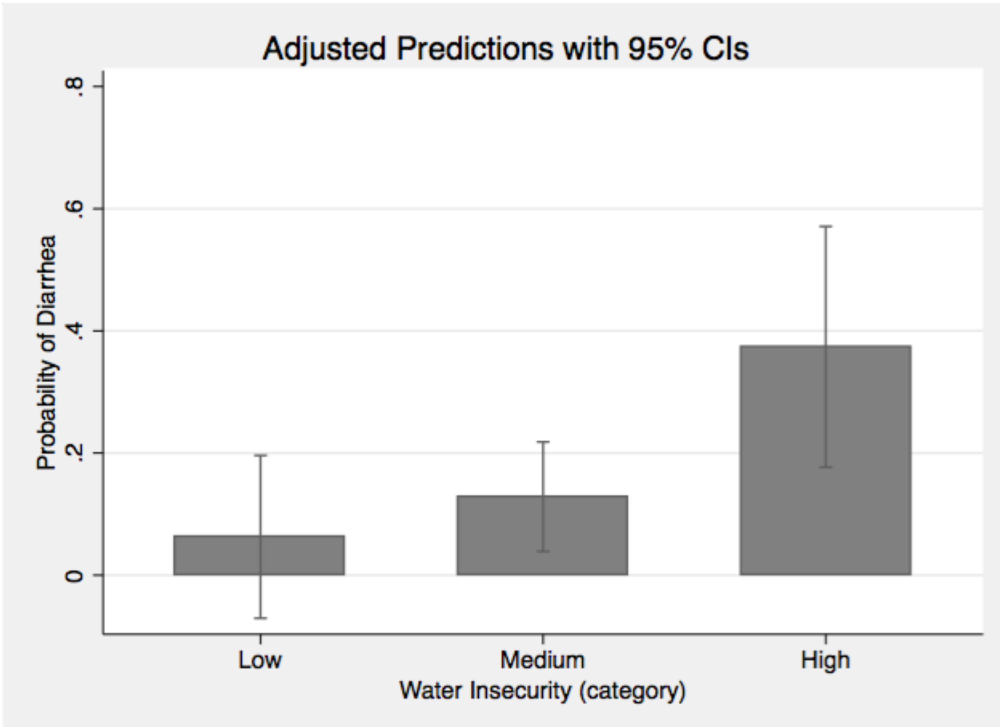

Figure 5.3: Predicted probability of diarrhea for adults based on their category of water insecurity adjusting for covariates in table 5.6 model 2.

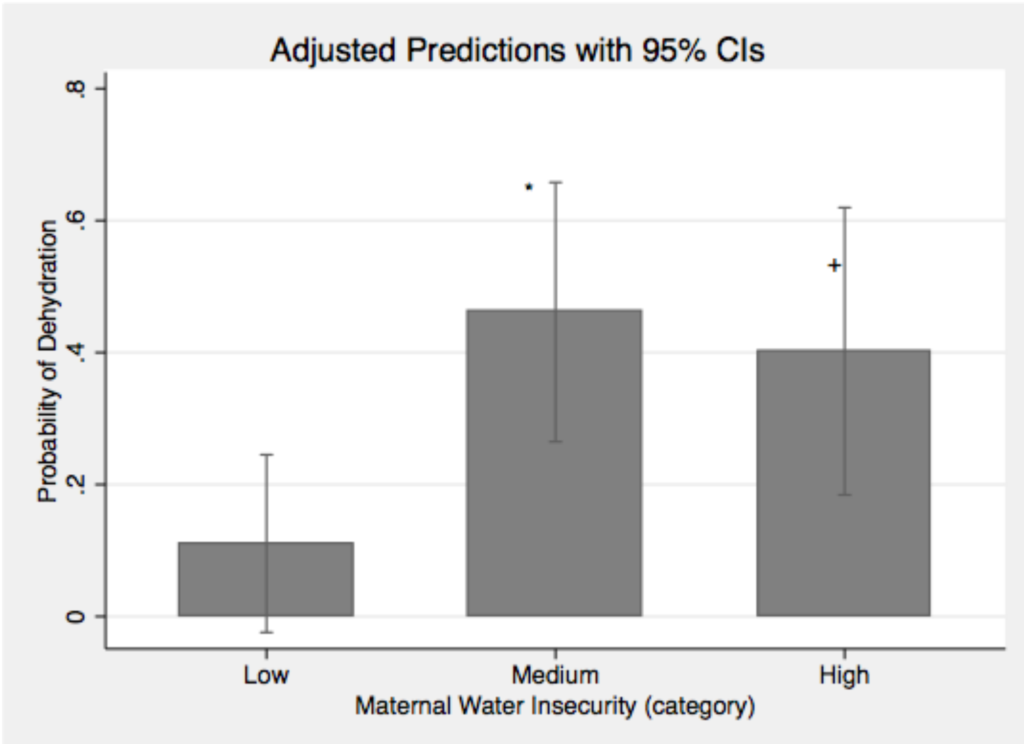

Figure 5.4: Predicted probability of dehydration for children by maternal water insecurity using covariates from Table 5.7 model 4.

CHAPTER 6

CONCLUSION

This dissertation has evaluated hydrations strategies, hydration patterns, lifestyle, and water insecurity in an effort to understand how humans with little access to clean water use, interact with, and perceive their environment, and in turn, how these dietary behaviors buffer stressors and mitigate tradeoffs between thermoregulation, hydration, and gastrointestinal disease. Theoretically, this dissertation has used a human adaptation perspective to assess how humans, in contrast to other mammals, meet their water needs in a hot-humid environment as they undergo rapid changes in lifestyle. The examination of water intake patterns during lifestyle transitions among extant humans is a critical topic of study because it sheds light on human responses, flexibility, and vulnerability to changing environmental conditions in a brief period of time. These changes may create an evolutionary mismatch and provide insights into other transitions in the history of *Homo* during critical periods.

This chapter provides a summary and synthesis of the main findings from the research presented in this dissertation. I begin with a discussion of the findings from Chapters 3-5. I then discuss the theoretical implications of the findings in terms of their contribution to the literatures in nutritional anthropology, human adaptability, and water insecurity. Next, I discuss these findings within the context of policy recommendations for international water references, the health implications of global climate change for the South American Amazon, and public health interventions. I close the chapter with future research questions that emerged from the findings of this dissertation.

Human water needs and nutritional adaptation

Chapter 3 investigated how Tsimane' meet their daily water needs and how different hydration strategies are associated with GI illness risk. The analysis indicated that a representative sample of Tsimane' adult men and women from one community consumed on average 4.9 L and 4.4 L of water daily, with water from food sources contributing 50% of the 24 hour total water intake. This finding is noteworthy because previous research in industrialized countries from the US, Europe, and Australia all suggest that food on average only contributes 20-30% of daily water intake (Kant et al., 2009; McLennan & Podger, 1998; Manz et al., 2012). However, the present dissertation indicates that individuals within populations can get as much as half of their water from food sources illustrating flexibility in hydration strategies.

After chapter 3 was published, another study was published indicating similar findings among Japanese adults. Tani and colleagues (in press) found that food makes up 51% of water in the diet for Japanese adults across four seasons. This study corroborates findings from chapter 3 and indicates that populations in different environments may get more water from food sources than international water recommendations generally suggest.

The second noteworthy finding from chapter 3 was that water from food sources was protective against risk of GI illness. As individuals in the sample consumed more than 43% of their water from food sources, their risk of GI illness dropped significantly below the baseline prevalence of GI illness. This finding provides potential evidence of a nutritional adaptation in an environment where access to clean water is scarce. In this manner, Tsimane' who consumed more water from food sources may have reduced their risk of pathogen exposure and GI illness.

Yet, individuals in follow-up interviews indicated that they modify their hydration strategies when sick with diarrheal diseases. Therefore, hydration strategies may be part of a cycle where they are both related to but also affected by risk of GI illness. This cycle of hydration strategies, water needs, water availability, and GI illness is one that is critical to understand as morbidity can persist leading to detrimental health and economic effects.

Hydration, heat, and lifestyle transitions

Chapter 4 investigated how differences in ambient temperature, lifestyle, activity levels, and body size relate to daily hydration rhythms of Tsimane' adults in two communities. Measuring temperature, hydration status, anthropometrics, and activity levels at four time periods (two periods sampled for each individual), the analysis indicated a gradual dehydrating trend throughout the day that resembled the phenomenon of voluntary dehydration. Forty-two percent of the participants met the clinical definition for dehydration and on average, the participants became dehydrated past mid-day and remained dehydrated at the last period sampled.

Ambient temperature was highly significantly associated with hydration status for both males and females as each degree C was associated with an increase of 0.001 g/ml of urine specific gravity, adjusting for measures of body size like height, weight, body fat, and BMI. Second, activity levels, which were not significantly different by village, were partially associated with hydration status. Finally, the analysis indicated that individuals living in a close community to the major market town in the region were significantly more dehydrated than individuals living in the distant village.

Water insecurity

Chapter 5 examined the predictors and health outcomes of water insecurity of Tsimane' following a historic flood. The analysis indicated that 89% of the sample reported medium or high water insecurity. The three predictors of water insecurity were primary water source, age, and village membership. Individuals who used the hand-pump well reported significantly lower water insecurity than individuals who used the river on a daily-basis. Second, younger adults reported higher water insecurity than older adults. Finally, adults from the close village had marginally higher water insecurity scores than adults in the distant village.

The second important finding from this chapter relates to the health outcomes associated with water insecurity. Examining water insecurity as a categorical variable, adults who reported high levels of water insecurity were nine times more likely to have suffered from diarrhea in the previous week than adults who reported low water insecurity. However, high water insecurity was not associated with risk of dehydration for adults. Conversely, medium and high maternal water insecurity was associated with a 6.5 and 5.5 fold significantly higher risk of dehydration among children 12 years or younger compared to kids whose mothers reported low water insecurity. However, high maternal water insecurity was not associated with children's risk of diarrhea.

Theoretical implications

Overall, the findings illustrate the degree to which humans interact with their environments plays a critical role in acquiring water in the diet, risk of GI illness, and hydration status, but that lifestyle transitions may affect all of these factors. These findings contribute to understanding human adaptation and flexibility to resource scarcity during changing environments. Humans can extract more than half of their water from food sources, but this appears to change as they undergo dietary transitions and may have implications for hydration patterns. Moreover, perception of the water environment can provide a window into how individuals experience their water environment and disease ecology and can serve as a proxy for risk of diarrheal diseases and dehydration.

Nutritional anthropology begins from the premise that diet bridges the environment, culture, and human biology (Pelto et al., 2000; Leonard, 2012). This literature investigates how humans use their diet and dietary techniques to buffer environmental stressors (Ungar et al., 2006). The findings presented in chapter 3 extend the existing literature regarding human use of dietary strategies to flexibly meet macronutrient needs by providing evidence describing a similar phenomenon concerning the essential macronutrient, water, through hydration strategies (Stinson, 1990). The flexibility to be able to utilize water from fruits and foods not only contributes water to daily intake, but can reduce the risk of exposure to pathogens when access to clean water is limited through substitution (eating a papaya instead of drinking dirty water) or through processing (making a soup through which the water is boiled). These findings echo sentiments from researchers who describe apples as containers of clean water and cider and gruel fermentation techniques as ways to render dirty water drinkable (McClatchey & Reedy, 2010).

Moreover, nutritional adaptations are critical to understand, because it is extremely costly to make genetic changes or physiological adaptations when dealing with environmental constraints (Haas & Harrison, 1977). Nutritional adaptations are part of a set of culturally and behaviorally integrated buffers that humans use to minimize the effects of ecological stressors like disease load (Stinson, 1990; Frisancho, 1993). Dietary traditions and behaviors are relative to the local environment, such that traditions often arise out of responses to the available local resources and environmental constraints (Huss-Ashmore, 2000). This dissertation adds to this theoretical approach by examining water holistically within the diet and in relation to the disease pressures. In this environment where clean water is scarce and there is a high prevalence of GI illness and parasites, consuming water from water-rich fruits and boiled soups may take longer than drinking river water, but this hydration strategy, part of the local dietary tradition, may be ultimately protective against pathogen exposure.

Next, hydration status is a homeostatic process that is always in flux (Armstrong, 2007). Human biology and adaptation research have hypothesized that native populations from hot-humid environments are better able to buffer heat stress than acclimatized non-native populations (Frisancho 1993). This research suggests that these advantages are through genetic adaptation, acclimatization, or behavior. Most research argues that all humans are equally able to, over weeks to months, modify sweat rates to minimize water loss and improve health, yet native populations appear better adapted through lower heart rate increases during work (Hanna & Baker, 1974). Little recent research has evaluated hydration patterns in a population living in a hot-humid environment (Hanna & Brown, 1983). The findings from chapter 4 illustrate the tight connection of internal hydration state with ambient environmental conditions, like temperature variation, for a native population. Yet, this connection reveals the difficulty of buffering dehydration risk in a hot-humid environment even for a native, acclimatized population. It remains unclear, however, if native populations have better water balance during humid heat than acclimatized, non-native populations, especially during work outputs.

All mammals are able to concentrate urine to deal with water scarcity (Beuchat, 1996). The findings from chapter 4 contribute to human adaptability literature by indicating that humans like other mammals have developed physiological adaptations to many local environmental pressures, like humid heat, and not just aridity. The daily hydration patterns exhibited by

Tsimane' reflect voluntary dehydration as adults become gradually dehydrated throughout the day. Humans are not efficient at storing water, and therefore the adaptation of voluntary dehydration may be important to remain productive throughout the day rather than stopping work to constantly drink or eat (Noakes, 2010; Hanna & Brown, 1983). However, voluntary dehydration does not appear to be a uniquely human trait as research on bird migration shows that they become dehydrated during their trips (Sapir et al., 2004; Tsurim et al., 2008).

A departure from a lifestyle more congruent with evolutionary conditions to a more modern one may be detrimental to health (Eaton & Konner, 1985), but *Homo* has shown flexibility with marked variation in the responses to environmental change as some societies have thrived and some become extinct (Baker et al., 1986). A significant amount of literature has shown that lifestyle transitions among living people in the past several decades are associated with changes in weight, body composition, and disease patterns, like increased risk of obesity, diabetes, hypertension, and cardiovascular disease (Baker et al., 1986; Lourenco et al., 2008; Abou-Rbiah & Weitzman, 2002). To the author's knowledge, the findings from chapter 4 illustrate for the first time that another unintended consequence of lifestyle transitions may be an increased vulnerability to dehydration. This increased risk of dehydration may be due to diet differences (relying on mixed raw water for beverages and frying foods over traditional drinks and meals) and environmental modifications that accompany lifestyle transitions leading to work in different environments (under the hot sun in slash and burn horticulture fields versus under the forest canopy). Expanding the literature on the health effects of lifestyle transitions provides a better understanding of past and future changes human populations have undergone and continue to undergo (Aiello & Anton, 2012).

Finally, chapter 5 broadens the paradigm of water insecurity in two ways: by examining it in a water-rich environment and by looking at salient health outcomes. First, the majority of research on water insecurity examines this construct in water scarce conditions. This dissertation adds to this literature by examining water insecurity in a water-rich area that lacks access to clean water. The theoretical implications of the findings from chapter 5 suggest that individuals living in water-rich environments without access to clean water are also "suffering from water" (Ennis-McMillan, 2001). The perception of water insecurity and uncertainty then may come about when proper allocation, distribution, and consistent access to clean water is unavailable even when there is an abundance of water. This finding has implications for millions of individuals who live in flood-prone regions as they may be experiencing similar psycho-social stress to individuals living in water-scarce conditions, associated with the three dimensions of water insecurity (Stevenson et al., 2012).

Second, while previous research in water insecurity has examined how water insecurity is associated with mental health outcomes, like suffering from water, frustration, anxiety, and anger (Ennis-McMillan, 2001; Wutich & Ragsdale, 2008; Stevenson et al., 2012), little research has examined the relationship between water insecurity and the health outcomes associated with a lack of access to clean water (Wutich & Brewis, 2014). This dissertation extends the connection between water insecurity with risk of diarrhea and dehydration. While the results are mixed, the findings in chapter 5 indicate that perception of water insecurity may be used as a proxy for risk of diarrhea for adults and risk of dehydration for children. While perception of water insecurity may be more acute when an individual or their children are suffering from diarrhea and dehydration, the link between the two suggests that water insecurity in this context captures a key perceptual connection between the water environment and health outcomes.

Policy implications

The findings from chapters 3-5 have important policy implications related to water recommendations, health effects of climate change, and public health interventions.

First, international water recommendations should take into consideration that many areas lack access to clean water, that water needs may be much higher depending on the temperature and activity levels, and that subpopulations like lactating women are particularly at risk for dehydration (IOM, 2004; ESFA, 2010). The Institute of Medicine's (2004) water recommendations for men (3.7 L) and women (2.7 L) underestimate the amount of water Tsimane' consume due to differences in ecological conditions, physical activity levels, and temperatures. Similar to Leonard's (2002) call to make dietary recommendations region-specific, this dissertation makes a similar call that water recommendations should be regionally specific to allow for cultural differences in dietary and beverage traditions as well as variation in ecological conditions.

Second, this research also provides health implications for a key facet of climate change: increasing temperatures (Magrin et al., 2014). While chapter 4 only presents data on weather, which does not equate to climate, extrapolations of the results suggest that hotter temperatures in the Amazon, which will move the average temperature above the thermoneutral range, will increase the risk for dehydration among rural populations. The majority of populations living in rural areas do not depend on climate control methods apart from behavioral and cultural buffers, like activity scheduling. These populations may suffer increased morbidity due to heat waves and hotter temperatures (Lundgren et al., 2013). Understanding the potential for increased morbidity may help governments plan accordingly to attempt to temper the effects of increasing temperatures through activity guidelines, such as restricting work during extreme temperatures.

Finally, the research on water insecurity suggests that younger individuals and those living in a close village to a main market town reported higher water insecurity. These findings suggest that exposure to public health messages may be affecting the perception of water cleanliness and as a result, that younger adults and those living in areas close to market towns may be rating their water as dirtier or unacceptable, whereas older adults who have more experience living in this water environment may not have the same preoccupations about consuming river water.

The policy implications of these findings are complex. It is positive that there are efforts by NGOs to improve access to clean water for Tsimane'. Yet, if only knowledge is given without the means to treat water, certain individuals within villages may feel helpless and suffer worse morbidity. For example, within the close community, there are groups of families that live on the far side of the river where no wells or hand pumps are present and their only sources of water remain the river and streams. For them, crossing the river to collect 5-20 liters of water from the wells or pumps multiple times a day is impracticable. They see others in their community utilizing the cleaner sources of water and when they are sick or their children are sick with diarrhea, they suffer a double whammy of perceptional and health inequality.

Therefore, it is this author's recommendation that public health interventions that intend to provide access to improved water sources do so in a way that benefits the majority of individuals in a village, but that they also stress the clean water potential of fruits and local fermented beverages for hydration purposes. While the placement of wells and pumps is a political process, as individuals with power will attempt to get favorable placement closest to their homesteads, it is critical to build them in areas that reduce inequalities and serve the greatest number of individuals. Public health interventions should identify locations that have appropriate hydrology with high ground water tables that have low risk of being flooded, but that are also in areas where current access to clean water is limited, such as the far side of the river.

Future questions

This dissertation raises further questions about the evolution of human water needs as well as questions relating to human plasticity and ontogeny in response to water scarcity. The level of adaptation to humid heat remains unclear, i.e. if native populations have better water balance during humid heat than acclimatized, non-native populations, especially during work outputs. Additionally, while I found patterns of daily voluntary dehydration, it is unclear whether these patterns are associated with functional consequences affecting work performance and productivity. Moreover, if this pattern is repeated on an almost daily occurrence in early childhood, does this affect the development of the kidney and create greater or worse concentrating ability of urine? I found that Tsimane' get half of their water from food sources, yet did not link their hydration strategies to actual hydration status. It will be important moving forward to track how these strategies relate to water balance.

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APPENDIX A

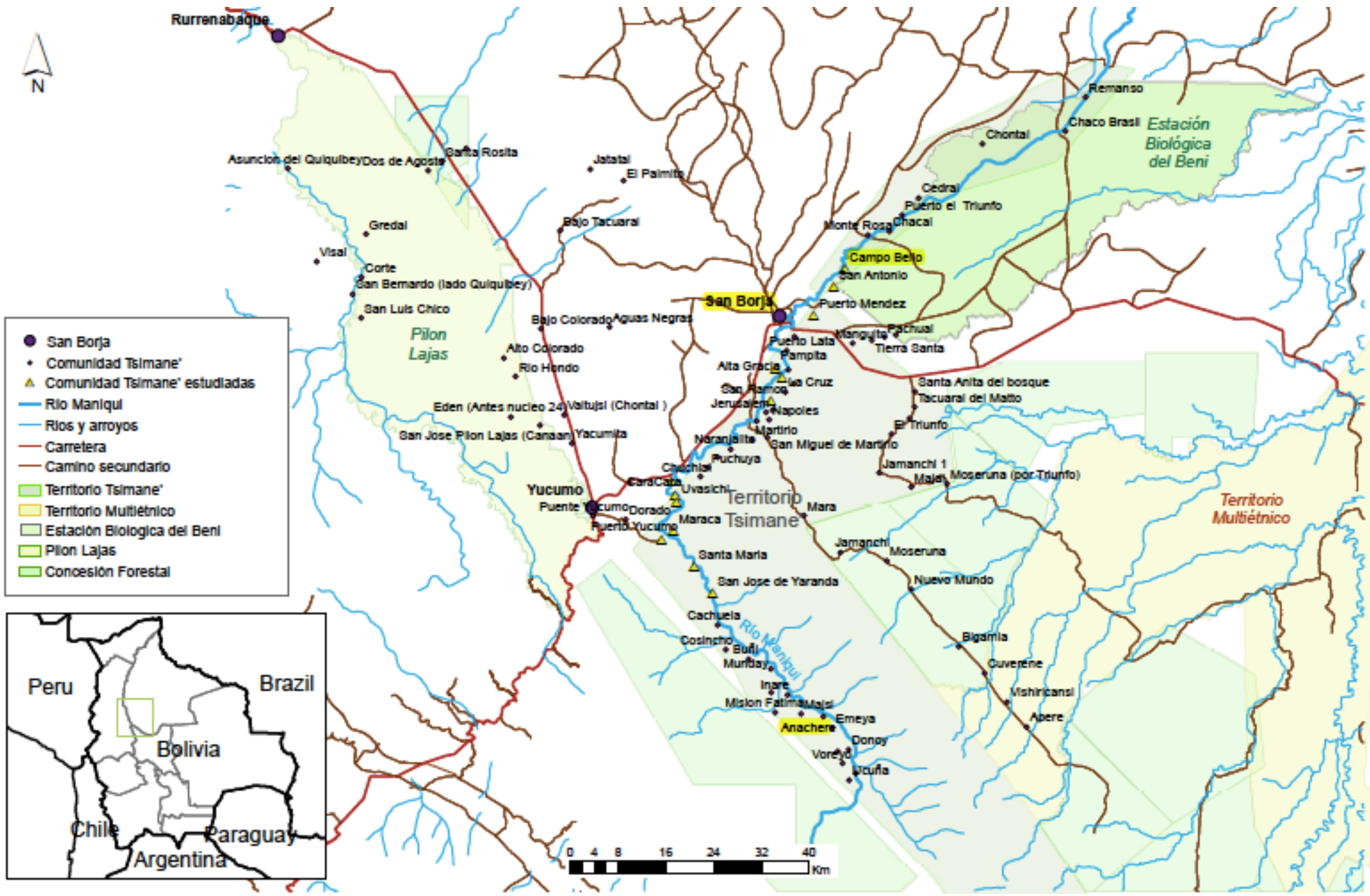

Figure A1. Map of field site and study communities.