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Primatological models for human nutrition: Lessons from the feeding ecology of howler monkeys

Modelos primatológicos para la nutrición humana: Aprendizajes desde la ecología alimentaria de los monos aulladores

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Abstract

In a global scenario marked by the loss of dietary diversity and the rise of metabolic diseases, there is an urgent need to reconsider the biological and evolutionary foundations of human nutrition. Nutritional anthropology incorporates comparative models with non-human primates to understand how dietary patterns are regulated in diverse environmental contexts. From this perspective, we propose that primates such as howler monkeys (Alouatta spp.) may serve as relevant models for understanding strategies of nutritional resilience in humans. Through an analysis of feeding ecology, dietary nutrient composition, secondary compound intake, and physiological adaptations, we argue that the trophic flexibility of howler monkeys reflects adaptive principles shared with humans, including protein leverage, prioritization of functional resources, and resilience in nutritionally constrained environments. This comparative approach seeks to enrich our understanding of dietary and nutritional transitions in humans, particularly in rural communities or those at risk of dietary homogenization, as recently documented in studies on the traditional Mexican diet. Finally, we advocate for a stronger integration of primatology, nutritional ecology, and nutritional anthropology to develop interdisciplinary frameworks that can inform and guide food policy development.

Keywords: nutritional ecology, non-human primates, dietary transition, biocultural conservation

Resumen

En un escenario global caracterizado por la pérdida de diversidad alimentaria y el incremento de enfermedades metabólicas, surge la necesidad de repensar las bases biológicas y evolutivas de la alimentación humana. La antropología nutricional integra modelos comparativos con primates no humanos para entender cómo se regulan los patrones dietarios en contextos ambientales diversos. Desde esta perspectiva, proponemos que primates como los monos aulladores (Alouatta spp.) podrían significar modelos pertinentes para comprender estrategias de resiliencia nutricional en humanos. A través de un análisis sobre ecología alimentaria, composición nutricional de la dieta, consumo de compuestos secundarios y adaptaciones fisiológicas, argumentamos que la flexibilidad trófica de los monos aulladores refleja principios adaptativos similares al de los humanos, incluyendo el apalancamiento proteico, la priorización de recursos funcionales y la resiliencia frente a entornos alimentarios limitados. Este enfoque comparativo busca enriquecer la comprensión de algunos procesos de transición alimentaria y nutricional en poblaciones humanas, especialmente en comunidades rurales o en riesgo de homogeneización alimentaria como ha sido documentado en estudios recientes sobre la dieta tradicional mexicana. Finalmente, abogamos por una mayor articulación entre la primatología, la ecología nutricional y la antropología nutricional para generar marcos interdisciplinarios basados en la investigación y que orienten las políticas alimentarias.

Palabras clave: ecología nutricional, primates no humanos, transición alimentaria, conservación biocultural

Introduction

In recent decades, interest has grown in understanding human dietary patterns through an evolutionary, ecological, and biocultural lens. Nutritional anthropology examines how humans acquire, select, and metabolize food within specific historical, environmental, and sociocultural contexts (Cordain et al., 2000; Leonard, 2014). Human diets can be interpreted within the framework of dietary adaptation and the historical processes that have shaped both food availability and cultural dietary norms (Wen et al., 2024). In this context, the feeding ecology of non-human primates has provided a valuable framework for exploring the biological foundations of human nutrition (Felton et al., 2009; Milton, 2003).

Comparative research with primates has identified shared principles such as the prioritization of specific nutrients, homeostatic regulation of intake, and the selective consumption of secondary compounds with specific physiological functions. For instance, studies using the Western lowland gorilla as a model to infer ancestral nutritional patterns in humans, have elucidated the role of the large intestine and the fermentation of fiber-rich plant diets, offering important insights into the evolution of human digestive and metabolic health (Popovich et al., 1997). Likewise, the protein leverage hypothesis, proposed by Simpson and Raubenheimer (2005), has been explored in both non-human primates and contemporary humans, suggesting that low protein availability may drive the overconsumption of energy-dense foods.

Nutritional strategies in primates offer a valuable opportunity to understand dietary resilience under environmental pressure and resource limitation. These scenarios parallel the conditions faced by many human populations experiencing food insecurity or undergoing nutritional transitions. From this perspective, we propose that Mexican howler monkeys (*Alouatta pigra and A. palliata mexicana*) represent a valuable —yet underexplored —model for understanding food selection patterns, nutritional resilience strategies, and physiological responses to dietary variation resulting from changes in food availability. Throughout the text, we offer a critical reflection on the feeding and nutritional ecology of howler monkeys, highlighting their potential as a comparative model for examining human dietary patterns through the perspective of nutritional anthropology. Through an integrative approach, we examine the parallels between trophic shifts in non-human primates and contemporary challenges in human nutrition within the Mexican context, thereby contributing to the interdisciplinary dialogue among primatology, nutritional ecology, and biocultural anthropology.

What howler monkeys reveal about human nutrition

Howler monkeys (*Alouatta* spp.) are Neotropical primates of ecological significance providing essential ecosystem services, such seed dispersal that contributes to forest regeneration. In addition, they are notable for their ability to survive in highly fragmented environments, an increasingly common condition driven by agricultural and urban expansion (Aristizabal et al., 2019; Milton, 2003). This trait makes them valuable models for understanding how habitat loss affects food availability, dietary selection, and nutritional strategies.

From an evolutionary anthropological perspective, comparative studies of nutritional and dietary patterns between non-human primates and humans allow us to address key questions about how our ancestors may have adapted to landscapes with fluctuating resources, both in quantity and nutritional quality (Milton, 2003). Howler monkeys stand out for their ability to maintain nutritional balance through diets primarily composed of leaves, complemented by the strategic selection of fruits, flowers, and other plant parts (Behie & Pavelka, 2012; Milton, 2000). The dietary patterns of howler monkeys reflect a dynamic balance that can help us understand how human populations that maintain traditional diets based on local, non-industrialized foods, particularly in rural or indigenous contexts, cope with changes in food availability and nutritional resources (Popkin, 2006). This is especially relevant in communities undergoing dietary or nutritional transitions, which refer to progressive changes in eating and nutrition patterns generally associated with economic development, urbanization, globalization, and lifestyle changes (Popkin, 2006). This process involves a shift from traditional diets, such as those found in Mesoamerican populations, which are typically high in complex carbohydrates and fiber, toward modern diets rich in fats, refined sugars, and processed foods (Popkin, 2006).

Since their origins, human primates (*Homo sapiens*) have exhibited remarkable dietary selectivity, reflected in feeding patterns shaped by energy demands, nutritional requirements, ecological changes, and cognitive and social strategies for acquiring food (Hohmann, 2009; Lim et al., 2021). Food decision-making has historically been influenced by resource availability, integration of ecological knowledge, and cooperation among individuals (Hewlett, 2016; Raichlen et al., 2014). These behaviors have been evident since early human ancestors and persist today in hunter-gatherer societies, which exhibit variable and heterogeneous diets adapted to the spatiotemporal fluctuation of food resources (Cordain et al., 2000; Luca et al., 2010; Raubenheimer et al., 2014). However, the domestication of plants and animals during the Neolithic period marked a transition toward more homogeneous diets with reduced nutritional diversity (Luca et al., 2010). Today, globalization, agro-industrial policies, and the standardization of food systems have encouraged the consumption of ultra-processed food items, reducing the intake of natural foods, especially in urban settings, with adverse effects on metabolic health (Clark et al., 2012; Sánchez-Ortíz et al., 2022; Matos et al., 2021). Nevertheless, traditional diets persist in rural areas, particularly among Mesoamerican communities, where staple foods include maize, legumes, tubers, native vegetables, mushrooms, traditional fermented beverages, and animal protein (Valerino-Perea et al., 2019). These parallels may inform the design of public policies, biocultural conservation programs, and food security strategies that respect local ecological and cultural contexts, while promoting the sustainable use of natural resources and traditional knowledge.

The feeding ecology of howler monkeys: Beyond folivory

Traditionally, howler monkeys (*Alouatta* spp.) have been classified as folivores due to the predominant consumption of leaves in their diets (Chaves & Bicca-Marques, 2013). However, some studies have shown that their feeding habits are more complex, involving the selective integration of other food items such as fruits, flowers, shoot tips, and petioles, depending on seasonal availability (Righini et al., 2017; Aristizabal et al., 2019). Furthermore, sexual differences in food selection have

been observed, with males and females exhibiting specific preferences that may reflect differing nutritional requirements, particularly during pregnancy and lactation (Dias et al., 2011).

Seasonal fluctuation in food availability influences dietary composition, promoting an increase in the consumption of preferred items, such as fruits and flowers, during periods of abundance, and a greater reliance on leaves during times of scarcity (Aristizabal et al., 2016). These feeding patterns also vary depending on habitat quality; in fragmented environments, howler monkeys select foods that optimize their nutritional priorities, while in conserved habitats, their diets are more balanced and diverse (Behie & Pavelka, 2012; Cristóbal-Azkárate & Arroyo-Rodríguez, 2007). It has been demonstrated that the spatial distribution of food resources, particularly fruits, influences food selection strategies in *A. pigra* (Aristizabal et al., 2019), a condition that may affect group social dynamics and patterns of dispersion in these environments. Such food-related decision-making, driven by continuous assessment of resource quality and accessibility, shows strong similarities to the nutritional choices observed in humans in rural contexts, where diets are likewise shaped by availability, seasonality, and culturally accepted food preferences (Luca et al., 2010; Valerino-Perea et al., 2019).

Dietary strategies in response to habitat fragmentation and environmental change

Habitat fragmentation poses a significant challenge for howler monkeys, as it alters both the availability and nutritional quality of food resources (Arroyo-Rodríguez & Dias, 2010). Fortunately, howler monkeys exhibit dietary strategies to maintain adequate nutrient intake under changing and adverse environmental conditions. For example, Behie and Pavelka (2012) documented that after a hurricane, a population of *A. pigra* adjusted their food selection to balance essential nutrients such as proteins, carbohydrates, and minerals, thereby ensuring nutritional balance despite reduced resource availability. Moreover, it has been observed that the concentration of micronutrients in the diet, such as vitamins and minerals, varies significantly due to seasonal changes and habitat fragmentation. In response, howler monkeys actively modify the composition of their diet (Silver, 2000). The nutritional quality of howler monkey diets varies substantially depending on the environment, highlighting differences between food resources available in fragmented versus conserved habitats (Silver, 2000).

In *A. pigra*, food selection has been found to be influenced by the concentration of certain plant-derived biomolecules, with particular emphasis on the seasonal availability of lipids (Righini et al., 2017). Similarly, certain essential minerals (e.g., K, Na, and P) have significant effects on feeding strategies following extreme environmental disturbances, suggesting that these elements may support physiological recovery and help maintain reproductive continuity under physiological stress conditions (Behie & Pavelka, 2012). The above highlights the evolutionary importance of consuming specific micronutrients for reproductive health and the overall evolutionary success of primates (Milton, 2003). This perspective underscores the relevance of further exploring how these insights can be extrapolated to functional nutrition strategies in humans, particularly in rural and indigenous communities where access to conventional foods is limited or fluctuating (Andersen et al., 2014; Matos et al., 2021).

Evolutionary implications and anthropological applications

The active regulation of macronutrient and mineral intake in howler monkeys, particularly in degraded environments resulting from habitat fragmentation, demonstrates homeostatic control and selective feeding behavior. These feeding strategies are similar to those documented in traditional human societies (Simpson & Raubenheimer, 2005). Some animals, including humans, regulate their food intake primarily based on protein content (Felton et al., 2009; Simpson & Raubenheimer, 2005). Within this framework, protein-deficient diets can lead to an increased total energy intake, potentially promoting obesity and other metabolic disorders, an idea known as the "protein leverage hypothesis" (Simpson & Raubenheimer, 2005). There is evidence that, under normal nutritional conditions, human protein intake remains stable compared to other macronutrients, particularly in rapid nutritional and urban transitions (Bekelman et al., 2017). This mechanism may have played an evolutionary role both in food selection under wild, unpredictable environments and in current dietary trends leading to obesity in urban contexts (Bekelman et al., 2017). Rural communities undergoing nutritional transitions, for instance, in Mexico, face similar challenges due to an increasing exposure to processed and ultra-processed foods, resulting in the erosion of traditional dietary patterns and direct impacts on community health (Popkin, 2006). Anthropological studies highlight how these changes especially affect indigenous and rural communities in Latin America, which have traditionally consumed balanced diets based on local resources (Popkin, 2006; Uauy et al., 2001).

Future perspectives: Secondary compounds, physiology, and reproduction

Herbivorous mammals tend to select plants with high nutritional value (proteins and carbohydrates), while avoiding those containing harmful chemical compounds (secondary metabolites) (Ito & Hayashi, 2020). Food selection occurs not only among different tree species but also among individuals of the same species, within a single tree, and even among parts of a single leaf, reflecting chemical variation across plant items (Ito & Hayashi, 2020). High intake of tannins can be harmful to consumers, as these compounds may harm the mucosal lining of the digestive tract and negatively affect gastrointestinal bacteria (Serrano et al., 2009). Although most species consume plants selectively, some, such as howler monkeys, have developed certain tolerance to plant chemical defenses (e.g., tannins and flavonoids) (Espinosa-Gómez et al., 2013). The incorporation of these secondary compounds plays a key role in the dietary strategy and physiology of howler monkeys (Espinosa-Gómez et al., 2018). However, it is also known that these primates can strategically adjust their intake to mitigate the potential harmful effects (Espinosa-Gómez et al., 2018). On the other hand, flavonoid consumption is potentially beneficial not only for animals but also for humans, as these compounds exhibit strong antioxidant and anti-inflammatory properties and trigger various cellular processes that improve cellular health, general well-being, and even mental health (Cueto-Escobedo et al., 2020; Winter & Bickford, 2019).

Beyond their ecological role, secondary metabolites may have important effects on digestive physiology. In humans, these compounds are associated with gastrointestinal health benefits, like reducing inflammation and preventing microbial

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imbalances like intestinal dysbiosis (Martínez-Mota et al., 2023). Exploring these parallels between howler monkeys and humans could open new research avenues in comparative nutrition, particularly concerning how diets rich in bioactive compounds—such as traditional Mesoamerican diets—can support metabolic resilience. It is worth investigating whether the plant species selectively consumed by howler monkeys serve equivalent roles in the functional ecology of their digestive systems. Emerging research questions include: How similar are the microbiota responses in howler monkeys and humans to shared secondary compounds? Could the selection of certain foods reflect co-adaptive strategies with digestive microorganisms? These questions, in turn, may help identify functional foods in human diets that potentially enhance health, demonstrating the deep parallels that exist between human and non-human primates (Fiedor & Burda, 2014).

Synthesis and final considerations

Comparative analysis of howler monkeys and rural or nutritionally transitioning human communities reveals shared patterns of dietary regulation. For example, just as howler monkeys adjust their food selection to balance proteins, carbohydrates, and micronutrients in fragmented habitats, human populations that still follow traditional diets based on maize, legumes, and *quelites* in Mesoamerican regions employ strategic food selection and combination to optimize nutritional intake under conditions of limited availability. Likewise, both species incorporate bioactive compounds, such as tannins and flavonoids, from specific plant species into their diets, which can regulate gut microbiota and reduce inflammation. In howler monkeys, such selection appears to be driven by ecological pressures, whereas in humans, it is linked to cultural and sociopolitical processes such as the nutritional transition. Furthermore, both humans and howlers exhibit flexible responses to changes in food availability, reinforcing the notion that dietary decisions are not merely instinctual or cultural, but may also be adaptative in nature.

Finally, integrating novel primatological models into contemporary nutritional anthropology offers a promising approach to reframe current challenges such as the loss of dietary diversity, the erosion of traditional knowledge, and the rise of metabolic diseases associated with micronutrient-deficient diets. Therefore, we propose the following practical applications and research avenues:

- Design of resilient dietary strategies: Use the trophic selection model of howler monkeys to propose functional dietary combinations for human communities undergoing nutritional transitions or consuming carbohydrate and fat rich diets, with an emphasis in local foods rich in fiber, plant-based protein, and bioactive compounds.
- Prevention of metabolic diseases: Incorporate the concept of macronutrient regulation observed in primates into public health programs to prevent excessive intake of calorie-dense but micronutrient-poor foods, especially in contexts of dietary transition.
- Strengthening of biocultural conservation: Reassess the value of edible plant species for both humans and primates (e.g., wild fruits, young leaves, and flowers) as part of agroecological strategies that integrate biodiversity, food security, and local culture.
- Intercultural education in healthy eating: Develop educational material that highlights the parallels between the feeding ecology of howler monkeys and traditional Mesoamerican human diets, fostering a critical understanding of food through an ecological and evolutionary perspective.
- Innovation in digestive health research: Investigate the interaction between secondary metabolites and gut microbiota in primates as a basis for identifying functional foods that prevent dysbiosis and promote gastrointestinal health in humans, particularly in marginalized populations.

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