Title: The "weanling's dilemma" revisited: Evolving bodies of evidence and the problem of infant paleodietary interpretation

Short Title: The "weanling's dilemma" revisited

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Abstract

Breastfeeding is known to be a powerful mediator of maternal and childhood health, with impacts throughout the lifecourse. Paleodietary studies of the past thirty years have accordingly taken an enduring interest in the health and diet of young children as a potential indicator of population fertility, subsistence, and mortality patterns. While progress has been made in recent decades towards acknowledging the agency of children, many paleodietary reconstructions have failed to incorporate developments in cognate disciplines revealing synergistic dynamics between maternal and offspring biology. Central to this understanding has been heavy reliance on the "weanling's dilemma", in which infants are thought to face a bleak choice between loss of immunity or malnutrition. Using a review of immunological and epidemiological evidence for the dynamic and supportive role that breastfeeding plays throughout the complementary feeding period, this paper offers context and nuance for understanding past feeding transitions. We suggest that future interpretative frameworks for infant paleodietary and bioarchaeological research should include a broad knowledge base that keeps pace with relevant developments outside of those disciplines.

Keywords: weanling's dilemma, paleodiet, breastfeeding, childhood nutrition, immune ontogeny

Introduction

The last thirty years have seen a rapid evolution in understanding of the complex biological and cultural mechanisms involved in human lactation, early life nutrition, and their effects on health throughout childhood and the later lifecourse. The weight of evidence regarding the impacts of breastfeeding on global health has consequently formed a topic of discussion in recent years in high-profile medical publications, such as the *Lancet* (Rollins et al., 2016; The Lancet, 2017; Victora et al., 2016). Despite these scientific advances, research into the health effects of breastfeeding remains contentious and emotive in WEIRD (Western, educated, industrialized, rich, and democratic) counties, where breastfeeding is both idealized and vilified, and artificial infant feeding practices influence cultural norms (Tomori, Palmquist, & Quinn, 2018b). Some of this cultural tension is exemplified by varying perspectives on lactation within feminist theory, as breastfeeding has been cited as both a form of reproductive empowerment and a means of societally disenfranchising mothers (Hausman, 2013; Olson & Simon, 2019; Smith, Hausman, & Labbok, 2012). Anthropological scholarship is uniquely well-placed to address controversies arising from the interplay between biology and culture, and recent years have witnessed a renaissance in cross-disciplinary collaboration among researchers addressing breastfeeding and the mother-infant nexus (e.g. Gowland & Halcrow, 2020; Tomori, Palmquist, & Quinn, 2018a). Consequently, many social and biological anthropologists have integrated emerging knowledge from

lactation medicine, immunology, and epidemiology to inform their research designs and interpretations. However, not all subfields of anthropology have kept equally up to date with evolving data.

We argue that bioarchaeology generally, and paleodietary study in particular, would benefit from greater integration of lactation physiology, immunology, and understanding of variation in biobehavioral practice into interpretation. Where gaps between inference and evidence exist, in many respects these are not surprising. Paleodietary researchers are asked to acquire competence in a broad array of areas, including skeletal biology, biogeochemistry, issues of subsistence and technology, ecology, landscape and settlement archaeology, and cultural history among others. Emphasis in paleodietary training has not traditionally focused on also understanding contemporary developments in epidemiology, clinical nutrition, or immunology, likely because of the difficulty in training across such a broad swath of disciplines. Nonetheless, shortfalls in these areas of understanding have specific impacts on the interpretations made by paleodietary researchers. In a discipline that developed with a processualist ethic, application of unconscious cultural or theoretical assumptions by bioarchaeologists may be masked by a false sense of objectivity (Kendall, 2017). Lacking empirical counterpoints to unconscious ethnocentrism, such as cross-cultural data on human biological and behavioral variability, researchers are at risk of uncritically transmitting present expectations into past contexts. Nowhere is the impact of an information gap in bioarchaeology more marked than in the prevailing application of the weanling's dilemma in bioarchaeological interpretation.

The theory of the *weanling's dilemma*, a term first coined by health researchers seeking to define best dietary practice for children in economically poor nations (Rowland, Barrell, & Whitehead, 1978), posits that infants face a crisis point by the middle of their first year of life, in the following terms. Exclusive breastfeeding provides a microbiologically safe and nutritionally complete food for young infants in the early months of life, as well as immunological protection. However, sometime around the middle of the first year of life, fetal stores of hemoglobin become exhausted, as breast milk contains little iron. While the precise timing of iron deficiency risk varies, based on variables such as birth weight and cord clamping practices, current guidelines suggest that by six months of age nearly all infants will require supplementary iron (Pérez-Escamilla, Buccini, Segura-Pérez, & Piwoz, 2019). At this point, complementary foods must be introduced, which, in non-hygienic settings, are likely to be microbiologically unsafe. The dilemma thus faced is a choice between nutritional deficiency or exposure to pathogens.

Consequently, many bioarchaeological studies have depicted the period of complementary feeding as being the most perilous of a young child's life; it has been asserted that the protective benefits of breastfeeding become insignificant beyond the exclusive breastfeeding phase, and that maternally-provided passive immunity is lost beyond this stage (e.g. Dittmann & Grupe, 2000; Domínguez-Rodrigo et al., 2012; Katzenberg, Herring, & Saunders, 1996). Whilst the action of exogenous antibodies, such as those transferred placentally or via breastfeeding, belong to a type of immune function that is correctly termed "passive" in medical usage (in contrast to endogenous "active" immunity), non-technical usage by bioarchaeologists risks misconceptions relating to the linguistic connotations of the word in common parlance. These misconceptions, which are often based on outdated lactation science and conceptualize children as inactive recipients of a unidirectional maternal product, do not address the dynamic collaboration between maternal and offspring physiologies. Breastfeeding powerfully impacts the health of mothers as well as children, affecting hormonal regulation, facilitating mother-infant bonding, reducing disease risk, and

offering psychological and emotional benefits (Godfrey & Lawrence, 2010). However, we will focus here on the impacts of breastfeeding for children, as these pertain directly to the problems posed by the weanling's dilemma. Assumptions regarding the inert receptivity of the offspring role in breastfeeding do not occur in a vacuum, as children in archaeology have traditionally been portrayed as passive (where they are portrayed at all), rather than actors exerting agency (Kamp, 2001; Sofaer Derevenski, 2000).

In addition to being viewed through a lens of passivity, children in archaeological studies deemed to have breastfed beyond early infancy have also been regarded as being inherently and paradoxically vulnerable to poorer health. Past anthropometric research linked longer periods of breastfeeding alongside complementary foods in non-industrialized societies with undernutrition and poorer health outcomes, serving to crystallize an inferred causal relationship between "prolonged" breastfeeding and increased risk of child stunting and malnutrition (e.g. Brakohiapa et al., 1988; Briend & Bari, 1989; Victora, Vaughan, Martines, & Barcelos, 1984). Consequently, while some key paleodietary studies have acknowledged the immunological and nutritional benefits of continued breastfeeding beyond early infancy (e.g. Eerkens, Berget, & Bartelink, 2011; Judd et al., 2018; Waters-Rist, Bazaliiskii, Weber, & Katzenberg, 2011; Wright & Schwarcz, 1998), others have continued to associate breastfeeding of older infants and children with detriment to health status (e.g. Holder et al., 2017; Sandberg, Sponheimer, Lee-Thorp, & Van Gerven, 2014; White, Maxwell, Dolphin, Williams, & Longstaffe, 2006).

Problems associated with linking breastfeeding beyond infancy to malnutrition are compounded by imprecision in language. "Weaning" is defined as a process of transition away from exclusive dependence on breastfeeding and towards full reliance on non-breastmilk liquids and solid foods (Millard, 2000). Use of the term "weaning" has proved problematic in research, being sometimes used to describe a process of transition (complementary feeding) and other times used to signify an event (final cessation of breastfeeding). We therefore avoid use of "weaning" wherever possible, in favor of clearer use of "complementary feeding", which indicates intake of nutritive solids or liquids alongside breastfeeding, or "cessation of breastfeeding", which indicates the final end of breastfeeding at the end of the complementary feeding period (Agostoni et al., 2008).

Here, we examine the assumptions inherent to the weanling's dilemma, as expressed in bioarchaeological research. Being ourselves bioarchaeologists, our aim here is not to position ourselves as experts on topics outside of our discipline, present a merely negative critique of work within our discipline, or to overlook the value of past or present contributions. Rather, our goal is to constructively signpost evidence and expertise from outside our discipline which will ultimately enrich paleodietary interpretation and our understanding of the relationship between early life health and diet. In order to do this, we address three major questions. Firstly, is the immune protection offered by breastfeeding exclusively passive and unidirectional in nature? Secondly, are the biological impacts of breastfeeding significant beyond the introduction of complementary foods? And thirdly, does "prolonged" breastfeeding *per se* represent a risk factor for malnutrition?

This paper presents a review of the current state of knowledge on the immunological and dietary impacts of breastfeeding beyond early infancy and attempts to identify the causes of enduring misinformation. We also offer a reinterpretation of a published dataset to illustrate the interpretative potential created by integration of a broader cross-disciplinary knowledge base. Finally, we argue that research attempting to understand past infant feeding patterns must be firmly based in current evidence, and thus bioarchaeology would benefit from closer working relationships with researchers and data from cognate disciplines.

“Weaning” Studies in Bioarchaeology

The study of breastfeeding and early life dietary practices in past populations has developed over the last few decades. During that time, the focus of research, the questions posed, and the methods used to address them have shifted substantially. Early studies focused on the importance of the complementary feeding period for infant mortality and the implications of each for maternal fecundity and population demography, rather than the life experiences of children as agents (e.g. Bentley, Goldberg, & Jasienska, 1993; Buikstra, Konigsberg, & Bullington, 1986; Holland, 1989). Among archaeologists, the complementary feeding period, in keeping with anthropometric studies of the time, was envisioned as being an intrinsic source of physiological stress, termed simply “weaning stress”. Accordingly, “weaning” was widely implicated in the development of skeletal markers of developmental arrest, particularly enamel hypoplasia (cf. Corruccini, Handler, & Jacobi, 1985; Goodman, Armelagos, & Rose, 1984), without clarification regarding which stage of the process was expected to produce such stress.

From the late 1980s, developments in biogeochemical analytical techniques such as carbon and nitrogen stable isotope analysis provided a more direct means of inferring breastfeeding practices in past populations, methods heavily exploited by archaeologists. The isotope ratios of organisms throughout the food chain are determined by both the ratios of their environmental inputs (DeNiro & Epstein, 1978; DeNiro & Epstein, 1981), and further fractionation resulting from *in vivo* metabolic activity (Minagawa & Wada, 1984). This leads to enrichment in the heavier isotopes at each stage in a food-chain, known as the trophic level effect (Schoeninger, 1985; Schoeninger & DeNiro, 1984). Such an increase should also occur in the isotope ratios of tissues of breastfeeding infants, as the breastmilk they are consuming is a product of their mother’s body. Observational studies sampling fingernails or hair of modern mother-infant pairs have demonstrated elevated $^{13}C/^{12}C$ and $^{15}N/^{14}N$ ratios among exclusively breastfed infants, relative to those of their mothers (Fogel, Tuross, & Owsley, 1989; Fuller, Fuller, Harris, & Hedges, 2006a). The principle of mother-infant trophic level tissue effects in breastfeeding observed for keratinized tissues have been inferred to also occur in skeletal tissues such as bone and tooth collagen. Isotope ratios plotted against age at death (e.g. Dittmann & Grupe, 2000; Fogel et al., 1989; Gardner, Bartelink, Martinez, Leventhal, & Cambra, 2018; Schurr, 1997) and, more recently, age of tissue formation in dentine (e.g. Beaumont & Montgomery, 2015; Craig-Atkins, Towers, & Beaumont, 2018; Eerkens et al., 2011; Fuller, Richards, & Mays, 2003) are used to establish infant dietary patterns of populations or individuals.

By the turn of the twenty-first century, stable carbon and nitrogen isotope analyses of collagen had achieved primacy in assessing past breastfeeding patterns. These studies shifted from the earlier focus on agricultural transitions towards understanding life-histories, with a high value placed on the social and historical context of past lives (e.g. Halcrow et al., 2018; Haydock, Clarke, Craig-Atkins, Howcroft, & Buckberry, 2013; Howcroft, Eriksson, & Lidén, 2012; Kaupová et al., 2014; King et al., 2018; Knudson & Stojanowski, 2008; Larsen, 2002; Wright & Yoder, 2003). In this framework, paleodietary data have become integral to informing interpretations of archaeological population health, particularly within the realm of nutritional deficiency and physiological stress. The impacts of breastfeeding on population health have formed an area of particular concern, intensified by the emergence and integration of epidemiological interpretative frameworks suggesting the programming effects of early life health and diet, such as the Developmental Origins of Health and Disease (DOHaD) hypothesis (Barker, 2004).

Interest in the timing of fluctuating nutritional and disease states during early life has largely driven the development of higher-resolution methodologies in archaeology that allow a longitudinal approach and complement a life-history emphasis. These developments have been instrumental in revealing and addressing many existing biases in method, and in creating new avenues of enquiry for paleodietary researchers (cf. Beaumont et al., 2018; Beaumont, Montgomery, Buckberry, & Jay, 2015). Advances which complement the use of higher-resolution stable carbon and nitrogen isotope analyses include the introduction of newer analyses such as stable isotopes of sulfur (e.g. Howcroft et al., 2012; Nehlich et al., 2011) and calcium (Reynard, Pearson, Henderson, & Hedges, 2013; Tacail et al., 2017), as well as high-resolution elemental analysis under histological control (e.g. Li et al., 2020; Müller et al., 2019). The developments in this field, range of available methods, and current limitations have been ably reviewed elsewhere (Britton, 2017; Humphrey, 2014; Reitsema, 2013; Reynard & Tuross, 2014; Tsutaya & Yoneda, 2015). However, here our goal is not to critique paleodietary methods. Rather, we hope to thoughtfully reconsider interpretive assumptions frequently applied to data. In particular, while the agency of children and the importance of early life diet are now frequently acknowledged within bioarchaeology (e.g. Gowland, 2018; Halcrow & Tayles, 2008; Kendall, 2017; Perry, 2005), a robust understanding of breastfeeding as a complex systemic interface is still visibly absent from much of published bioarchaeological research and should be addressed.

More Than Nutrition, More Than Passive Immunity

Researchers in clinical medicine have explicitly suggested that, due to the weight of evidence for the immunomodulating and metabolic impacts of breastfeeding, it is important for public health and patient education programs to counter the prevailing and reductive view of breastmilk as “merely nutrition” (Ballard & Morrow, 2013: 54; Labbok, Clark, & Goldman, 2004; Maycock et al., 2015). In this view, human milk is conceptualized as a disembodied product to be delivered, rather than the result of embodied and interactive processes (Ryan, Team, & Alexander, 2013; Van Esterik, 1996, 2002). Arguably, this conceptualization has diminished, or even prevented, public perception of the dynamic immunological function of breastfeeding as a two-way communicative process. Researchers working in the field of infant paleonutrition are undoubtedly influenced by these discourses within their own culture, and this may reduce the extent to which they hold an evidence-based understanding of the dynamic and formative impacts of breastfeeding practices on individual and population health across the life course. It is important that bioarchaeologists move away from a simplistic understanding of breastmilk as a product offering exclusively passive protections, to an understanding of the complexity of protection offered to infants by breastfeeding.

Boilerplate statements in infant paleodietary research regarding the role of breastfeeding in early life health are ubiquitous and have changed little over several decades. Most are problematically vague, referring only to passive protection of a temporary nature, which is curtailed with “weaning”. For example, von Heyking and Zintl (2016) argued that “a possible cause of the high stress level in this phase of childhood can be seen in the weaning phase and the loss of passive immunity involved…”. It is unclear from this and other ambiguously phrased papers whether the loss of passive immunity associated with “weaning” is assumed to occur with the introduction of complementary foods, the final cessation of breastfeeding, or throughout the transition in between. The interpretative morass created by this problem of terminology, with its problematic assumptions about the relationship between “weaning stress” and skeletal pathologies, has been critiqued on theoretical and methodological grounds (Halcrow et al., 2018; Katzenberg et al., 1996; Lewis & Roberts, 1997; Millard, 2000; Schurr, 1997).

However, other papers in bioarchaeology and paleodietary research appear to suggest a diminishing or lost nutritional and immunological benefit during the complementary feeding period (rather than at its completion), overtly asserting a decline in either the quality of milk or its benefits to the infant (e.g. Fernández-Crespo, Czermak, Lee-Thorp, & Schulting, 2018; Fuller et al., 2006a; Fuller, Molleson, Harris, Gilmour, & Hedges, 2006b; Herring, Saunders, & Katzenberg, 1998; von Heyking & Zintl, 2016; Kwok & Keenleyside, 2015; Ogden, Pinhasi, & White, 2007; Sandberg & Van Gerven, 2016). Katzenberg *et al.* (1996), as an early example, is skeptical regarding the immunological buffering of breastfeeding during the complementary feeding period:

> This [collection of archaeological studies showing increased infant mortality]...suggests that the immunological benefits of nursing do not necessarily protect the infant from environmental pathogens once infants are no longer nursing exclusively (Katzenberg *et al.* 1996: 191).

It is important to note that Katzenberg *et al.* (1996), while a landmark paleodietary publication that moved the field forward in multiple regards, continues – over two decades on – to be cited by more recent publications as a source for the immunological impacts of breastfeeding practices (e.g., Garland, Turner, & Klaus, 2016; Mays, 2016; Webb, White, Van Uum, & Longstaffe, 2015). Reference to dated secondary publications, which reflected knowledge at the time of writing, rather than more appropriate current offerings from primary infant feeding science, may help perpetuate assumptions pervading some aspects of bioarchaeological research. These assumptions require unpacking.

Immunological protections of breastfeeding, described in the bioarchaeological literature, are almost wholly reduced to the action of antibodies, especially secretory Immunoglobulin A. Immunoglobulin A (IgA) has two primary forms: serum IgA, found in blood, and secretory IgA (sIgA), which predominates among antibodies in the secretions of mucosal surfaces, such as those that line the respiratory and digestive tract (Leong & Ding, 2014). Antibodies were the first bioactive constituents of milk to be identified and still retain the greatest popular recognition. These are produced by B cells, which migrate from the maternal gut to mammary tissue, providing specialized protection against pathogens in the shared maternal-offspring environment (Brandtzaeg, 2003). Breastmilk antibodies do not enter circulation in significant numbers, instead offering defense at the mucosal level (Van de Perre, 2003). While all the major antibody subtypes may be found in milk, the most important of these are sIgA, IgG, and IgM. Secretory IgA comprises 90% of all milk antibodies (Bernt & Walker, 2001) and is of particular importance, as neonates are not thought to be capable of producing this antibody (Battersby & Gibbons, 2013). Independent IgA production develops rapidly during infancy but is not believed to reach adult levels until as late as 4-6 years of age (Weemaes et al., 2003). IgA accounts for much of the reduced rates of urinary, upper respiratory, and gastrointestinal infections in breastfed children (Hanson et al., 2009). These benefits are accompanied by a reduction in the risks of inflammation, tissue damage, and excess energy expenditure, all of which would be increased by an unguided, naïve immune response (Hanson et al., 2001; Hanson & Korotkova, 2002).

Protections offered by breastfeeding have also suffered from being depicted as a passive *process*, due to the perception of one-sided communication between the maternal breast and the infant gut. Elizabeth Miller has recently critiqued use of a framework wherein "...infants are relegated to a 'passive' role, represented as a series of tubes to be protected, with mothers' immune systems shaping their babies' health in her own image" (Miller, 2018: 26). This usage echoes overall passive constructions of childhood in archaeology, where children are assumed to be wholly subject to the agency of others. Past bioarchaeological

study has traditionally attributed the immunological effects of breastfeeding to the reception of a transferred substance (e.g. Humphrey, Dean, Jeffries, & Penn, 2008; Waters-Rist et al., 2011; Webb et al., 2015). However, Miller rightly points out that this model ignores the active synergy between infant and maternal immune systems, a system she terms "collaborative immunity" (Miller 2018: 27).

The mechanisms of communication between mother and infant systems are unclear, but retrograde flow of infant saliva into the mammary gland is hypothesized to produce reciprocal communication between the maternal immune response and offspring microbiota (Hinde & Lewis, 2015; Moossavi et al., 2019). Evidence of increases of immunological components in human milk in response to active infection in the nursing infant, but not the mother, provides some support for this theory (Riskin et al., 2012). The inherently collaborative nature of milk immunity is also underlined by recent studies demonstrating differences in milk composition and lower disease risk in breastfed infants, relative to those fed exclusively on expressed breastmilk where no oral-mammary communication occurs (Klopp et al., 2017; Moossavi et al., 2019). Understanding that breastfeeding represents activity at a systemic interface offers a much more sophisticated interpretative paradigm for future research into mother-infant nutrition and health, as it allows researchers to consider many interactive factors which are environmentally-mediated and excluded by a view of breastfeeding as unidirectional provision of a product.

In order to avoid a reductionistic understanding of milk immunity as wholly passive in its delivery and effects, the other players in the cast of infant immune ontogeny need to be included. Of these less-commonly-considered factors, many play much more complex and interactive roles than previously understood; some traditionally thought to have simple nutritive or growth-related functions are now known to have immune bioactivity (Hanson et al., 2009). Bioactive substances in breastmilk (see Table 1 for a non-exhaustive summary of factor types) are numbered in the hundreds to thousands, and understanding of how these biomolecules function continues to evolve (Ballard & Morrow, 2013). Infants are born with functional, if naïve, immune systems. Early life immune response is inelegant, energetically costly during periods of high growth-demands, and modulates inflammation poorly (Newburg & Walker, 2007). Consequently, the collaborative role of milk comprises the provision of required energy for growth, transfer of bioactive factors with protective immune activity, and accelerated development and regulation of the infant's own active immune response through immunomodulatory and anti-inflammatory factors (Miller, 2020).

While bioactive components of milk are too numerous to discuss exhaustively, factors such as lymphocytes, macrophages, human milk oligosaccharides (HMOs), bioactive peptides, fatty acids, hormones, and cytokines perform complex and varied roles in the maintenance of infant health through their roles in upregulation and downregulation of immune activity, activation and recruitment of innate host defense, and influence on the infant microbiome (Fernández et al., 2013; Field, 2005). For instance, microbes in human milk, such as probiotic bacteria, and the probiotic substances which feed them (e.g. HMOs) have been shown to downregulate expression of genes associated with inflammation, protecting the intestinal mucosa from injury (Wickramasinghe et al., 2015). Still other factors (Table 1) rely on interaction with the infant system to develop bioactivity, as in the case of HAMLET, a protein-lipid complex. HAMLET has precursors present in human milk as the protein α-lactalbumin, but only develops its antitumor and bactericidal properties after protein unfolding in the presence of oleic acid, during the digestive process (Hakansson et al., 2011).

Synergistic activity has also been observed to account for *in vivo* bioactivity at low concentrations in some breastmilk factors, behavior previously obscured by *in vitro* studies of isolated factors (Newburg, 2005). Although some of these factors serve predominantly antimicrobial functions, many others have systemic, metabolic, and immunomodulatory priming functions which have impacts beyond host defense, and even beyond the termination of breastfeeding (Berti et al., 2017). Indeed, some research is beginning to suggest that the developmental and immunomodulatory effects of breastfeeding may be transgenerational (Holmlund et al., 2010; Indrio et al., 2017; Palmer, 2011), blurring the distinctions of "self" and "other" further via this collaborative interface. A recent paper described the breastfeeding relationship as a "triad", with human milk forming the third component linking mothers and infants in a mutually co-adapting system (Bode, Raman, Murch, Rollins, & Gordon, 2020). Accordingly, it is difficult to sustain a view of exclusively passive immunological benefits of breastfeeding based on current evidence for milk immunology, which goes far beyond the mere temporary provision of maternal antibodies.

Moving towards a view of mother-infant immunity as a collaborative process, and away from an outdated model of breastfeeding as unidirectional transfer of a product, can make positive contributions to informing bioarchaeological interpretation. Firstly, one of the great strengths of breastfeeding as a reproductive strategy is its adaptability to environmental conditions, including pathogenic threats, which present themselves to the dyad. Understanding that breastfeeding offers more than a one-way transfer of antibodies, and that immune support is targeted to not only temporary protection, but also priming of future metabolic and immune function, is essential to understanding the role breastfeeding is playing in childhood health. Secondly, bioarchaeologists need to recognize the active role played by infants and children in their own early life health. The negotiated processes which occur behaviorally between mother and child, in terms of the frequency, intensity, and duration of breastfeeding and complementary feeding, are paralleled by reciprocal and systemic interaction and communication at the biomolecular level. Recognition of these processes allows for an entirely different bio-behavioral paradigm in which children are not passive recipients only, but active participants in their own states of health.

"Growing Up Milk": Does Breastfeeding During Complementary Feeding Matter?

In addition to limited views of the range of mechanisms at work in breastfeeding, perceptions of diminishing returns on its health benefits beyond six months of age suppose that there is a systematic qualitative decline: either in the composition of milk, or in the magnitude of its effects due to decreased intake. These views may be bolstered by widespread agreement that cross-sectional data demonstrate a dramatic decrease in total and bioactive proteins in milk during the first few weeks of lactation, followed by a much more gradual decline in total protein concentration through the first year (Ballard & Morrow, 2013; Lönnerdal, Erdmann, Thakkar, Sauser, & Destaillats, 2017; Mitoulas et al., 2002; Verd, Ginovart, Calvo, Ponce-Taylor, & Gaya, 2018). These changes in protein content parallel a decrease in protein requirements, per kilogram of body weight, for growth after the second month postpartum (Boudry et al., 2010). Despite the decline in total protein, its nutritive value remains stable, as reflected by a consistent ratio of essential amino acids to total amino acids (Lönnerdal et al., 2017).

In the cultural realm, language used in the promotion of formula milks targeted at older infants or toddlers (in order to subvert international codes on the marketing of breastmilk substitutes to infants under 6 months) may also create or promote cultural susceptibility to the view that human milk may become increasingly inadequate to needs during infancy (Harris & Pomerantz, 2020). Products which substitute for continued breastfeeding, and use language

which suggests developmental progress and advances in nutrition, are widespread in anglophone countries, frequently using phrases like “growing up milk” (e.g. Hipp Organic Growing Up Milk, UK; Aptamil Growing Up Milk, UK; Cow & Gate Growing Up Milk, UK; SMA Pro Growing Up Milk, UK) or names that otherwise specifically play on the idea of promoting growth (e.g. Go & Grow by Similac, US and Canada; Good Grow by Nestle, Canada; Enfagrow, US and Canada). Inhabiting spheres where such discourse is commonplace may influence the perceptions of researchers, who are themselves cultural participants.

Nonetheless, the story of changing mature human milk composition is not one of unidirectional decline, but of adaptability. In this sense, human milk is truly a “growing up milk,” as breastfeeding offers a non-static source of nutrition and immunity which is adaptable to the age, stage, and environmental conditions of the breastfed child. Factors such as sIgA remain high throughout lactation, while other components increase over time (Lönnerdal et al., 2017). Within cross-sectional studies, observations of bioactive factor concentrations are highly variable, underscoring the confounding effects of intra- and inter-maternal variability on interpretation of longitudinal trends. In contrast to perceptions of progressive and unidirectional decline, some studies have observed a slow decline in sIgA during the first six months, followed by rising levels thereafter (Goldman, Garza, Nichols, & Goldblum, 1982; Zhang et al., 2013). Furthermore, increases in immunoregulatory factors such as the cytokine interleukins and IgG over time imply a strategic shift from simple antimicrobial protection to increasing immunocompetence during the first year of life (Gao et al., 2012; Yilmaz, Saygili-Yilmaz, & Gunesacar, 2007). Just as breastmilk needs to be understood as a dynamic substance responsive to short-term pressures, adaptability in composition over the course of lactation is best understood as a feature, not a flaw.

In keeping with broader primate biology, past societies are believed to have commonly breastfed and engaged in complementary feeding over a period of years, rather than months (Sellen, 2009). As breastfeeding duration measured in years is non-normative in WEIRD societies, data regarding milk composition beyond the first year of life are limited. Nonetheless, existing evidence discredits the idea of systematically deteriorating nutritive and immunological qualities. A recent longitudinal study tracking milk composition beyond the first year of life found broad stability in the macronutrient content of breastmilk, even up to four years (Czosnykowska-Łukacka, Królak-Olejnik, & Orczyk-Pawiłowicz, 2018). Moreover, a direct correlation has been found between decreasing milk intake during the complementary feeding phase and increases in concentration of total protein and bioactive factors such as lactoferrin, lysozyme, sIgA, and HMOs (Czosnykowska-Łukacka et al., 2018; Perrin, Fogleman, & Allen, 2013; Perrin, Fogleman, Newburg, & Allen, 2017). This accords with previous findings of a rise in sIgA at around six months (Goldman et al., 1982; Goldman, Goldblum, Garza, Nichols, & Smith, 1983; Zhang et al., 2013), likely corresponding to the introduction of solid foods. Evidence for adaptive fluctuation of bioactive elements of breastmilk – in response to changes in environment, rather than to duration of lactation – certainly does not support the interpretation of diminishing immunological factors in milk during the complementary feeding period, due to either decreases in concentration or volume.

In terms of whether changing milk consumption patterns produce diminishing impacts on infants themselves during the complementary feeding period, it is useful to consider available longitudinal evidence on microbiota in breastfeeding children. The microbiome is emerging as an important factor in human health and host defense, including the role of human milk as a key determinant of the microbiome in early life and as an enduring

influence. Until a few years ago, studies indicated that the introduction of solid foods was the primary catalyst of the shift from a breastmilk microbiome to one more similar to those of adults (Fallani et al., 2011; Koenig et al., 2011; Voreades, Kozil, & Weir, 2014). Thus, it was assumed that continued breastfeeding exerted little influence over the infant gut microbiome once solids were introduced. However, recent metagenomic studies have consistently found that for infants exclusively breastfed for the first six months, a characteristic breastmilk microbiome persists beyond the introduction of solids, with the development of adult-like microbial flora deferred until full cessation of breastfeeding (Bäckhed et al., 2015; Carvalho-Ramos, Duarte, Brandt, Martinez, & Taddei, 2017; Forbes et al., 2018; Matsuyama et al., 2019). Thus, among dietary factors, it is the provision or withdrawal of breastmilk to the infant gut that most strongly shapes the microbiome. Knowledge of how the microbiome acts as a crucial mediator of short- and long-term immune responses and primer of healthy metabolic function is continuing to emerge, weighing against the categorization of breastmilk mechanisms as entirely passive or short-term.

In terms of practical benefit, as the adage goes, the proof is in the pudding. Exclusive breastfeeding for the first six months of life and complementary breastfeeding up until the age of two years of age is associated globally with reduced incidence of morbidity and mortality associated with ear, respiratory, and gastrointestinal infections, diabetes, SIDS, and childhood leukemia, with some protective effects continuing for years beyond the cessation of breastfeeding (Bahl et al., 2005; Ip et al., 2007; Kwan, Buffler, Abrams, & Kiley, 2004; Lamberti, Fischer Walker, Noiman, Victora, & Black, 2011; Lamberti et al., 2013; López-Alarcón, Villalpando, & Fajardo, 1997; Mamun et al., 2015; Sankar et al., 2015; Strand et al., 2012; Victora et al., 2016). Breastfeeding at the age of 12 months and beyond is also shown to be protective against a range of parasitic protozoan infections (Korpe et al., 2013; Mahfouz, El-Morshedy, Farghaly, & Khalil, 1997; Mølbak, Aaby, Højlyng, & da Silva, 1994b; Morrow et al., 1992). These include *Cryptosporidium*, *Giardia*, and amebiasis, associated with diarrheal disease and the potential for malnutrition and impaired growth.

Evidence for the protective effects of breastfeeding beyond the somewhat arbitrary limit of two years is sparse, but strongly suggestive of breastmilk having continued bioactive impacts. Several studies examining the health of children from the ages of 1-3 years in Guinea-Bissau found that breastfeeding was protective against diarrheal morbidity, and also that children weaned for reasons other than perceived health and readiness – particularly maternal pregnancy – were at much higher risk of death, irrespective of age within the cohort (Jakobsen et al., 2003b; Mølbak et al., 1994a; Mølbak, Jensen, lngholt, & Aaby, 1997). Up to three years, the maximum age covered (rather than the maximum age of benefit), children who no longer breastfed were shown to face a higher risk of diarrheal illness, a longer mean duration of illness, and a 3.5 times higher risk of death, compared to breastfed children (Mølbak et al., 1994a). This parallels findings that among malnourished children up to the age of 3 years in Bangladesh, breastfeeding reduces mortality risk (Briend & Bari, 1989; Briend, Wojtyniak, & Rowland, 1988).

As the bioactive elements of breastmilk persist throughout lactation, the relative benefits of continued breastfeeding through early childhood are also extremely likely to depend not only on changes to milk composition, but on individual robusticity, attained immunocompetence, and the level of risk in the surrounding environment. A 2003 study addressed the role of breastfeeding in ameliorating relative risk in Guinea-Bissau. This study compared the mortality risk of refugee children aged 9-20 months weaned during the first three months of a war with the mortality risk of similarly aged weaned children in the two years prior, and with breastfed children of the same age range during both periods (Jakobsen

et al., 2003a). When controlling for age, a six-fold increase in mortality risk was observed for weaned children during the conflict, relative to weaned children in the years prior, while no differences in mortality were seen between the breastfed war- and peace-time cohorts. Hence, cessation of breastfeeding earlier in childhood may present fewer risks in some circumstances than others; or, conversely, later cessation may offer greater or lesser levels of benefit dependent on circumstance and relative need. It is therefore important when discussing continued benefits of breastfeeding during early childhood to be aware of environmental hazard and life history variables which may predispose some children to greater exposure or vulnerability to infection than others, such as the effects of *in utero* stress on longer-term metabolic and immune function suggested by the DOHaD hypothesis (Barker, 2004).

In the same way that it is necessary that bioarchaeologists appreciate that the range of impacts on childhood health offered by breastfeeding involve more than passive immunity, it is essential that archaeologists understand that these mechanisms persist throughout lactation, including the complementary feeding period. This is highly relevant, as continued breastfeeding alters the calculus of risk versus benefit envisaged during the complementary feeding period in the weanling's dilemma, as understood in bioarchaeological literature. Previous paleodietary research has frequently defaulted to negative assumptions regarding children's disease risks during the complementary feeding period, and much of this can be traced to beliefs around the purported loss of passive immunity with the onset of complementary feeding. New interpretative models which do not dismiss real risks to childhood health, but which integrate an understanding of the continuing benefits of breastfeeding beyond early infancy – particularly to children in the most vulnerable circumstances – create a more balanced and evidence-based foundation from which to assess the role past infant-feeding practices played in childhood health.

"Prolonged" Breastfeeding and Deficiency

In addition to supposing a declining immunological benefit of breastfeeding, some bioarchaeologists have also construed continued breastfeeding as presenting positive risk. Principal among the purported risks of sustained (or the more value-laden "prolonged") breastfeeding is increasing probability of malnutrition and stunted growth. Papers asserting that sustained breastfeeding plays a causative role in observed skeletal pathology or early mortality are far from universal, as some bioarchaeological research has explicitly attributed increased growth or survivorship to continued breastfeeding (e.g. Mays, 2010; Wright & Schwarcz, 1999). However, attributions of risk are also not rare; long-term persistence of breastfeeding is often named as a contributor to morbidity and mortality in past populations, particularly in regard to malnutrition (e.g. Holder et al., 2017; Holland & O'Brien, 1997; Ogden et al., 2007; Sandberg et al., 2014; Sandberg & Van Gerven, 2016; Walker, 1986; Walker, Bathurst, Richman, Gjerdrum, & Andrushko, 2009). As with use of the word "weaning", the problematic terminology of "prolonged breastfeeding" in bioarchaeology specifies duration but is often unclear regarding implied exclusivity or lack thereof. Examples of such ambiguity in the literature are common, even in recent years:

> ...potentially higher morbidity and mortality in the older age induced by a nutrition shortage due to prolonged breastfeeding (Kaupová et al., 2014: 647)

and

> Prolonged breastfeeding does not adequately meet the nutritional demands of infants and can result in iron-deficiency and megaloblastic anemia, both of which may lead to the formation of porotic hyperostosis and cribra orbitalia (Ash et al., 2016: 7).

Such linguistic imprecision is problematic, where, deprived of context, statements may be equally interpreted as implying dietary exclusivity at advanced ages or that continued breastfeeding may compete with and displace valuable complementary foods. Children referenced in such archaeological studies may be several years old at death, ages to which survival on breastmilk alone is highly improbable and at which it would be difficult for their carers to prevent self-feeding. Further, the context of such statements is meaningful. We, as researchers, are not exempt from the cultural environments in which we live, work, and produce research. Continued breastfeeding *alongside complementary foods* has been perceived as a risk factor for malnutrition and delayed development in past anthropometric research (Briend et al., 1988; Victora et al., 1984) and continues to be viewed as such among much of the wider public (Zhuang, Hitt, Goldbort, Gonzalez, & Rodriguez, 2019). Therefore, it seems reasonable to briefly review the existing evidence about breastfeeding and nutritional status beyond six months, and to assess the validity of viewing sustained breastfeeding during complementary feeding as potentially detrimental *per se* to nutritional state.

Around the middle of the first year, infant body stores of iron and zinc become depleted, alongside low or reducing levels of iron, zinc, and calcium in breastmilk (Fewtrell et al., 2007; Kramer & Kakuma, 2012). At that point, the introduction of solid foods becomes necessary to augment intake of these micronutrients and overall caloric intake. The stomach capacity of young children is small, creating a demand for nutrient-dense foods, particularly those rich in iron and zinc (Dewey, 2013). High nutritional quality, rather than quantity, of complementary foods is imperative for rapidly growing young children. However, unfortified complementary foods in many settings are vegetable or cereal-based foods that have high phytate levels, interfering with absorption of iron, zinc, and calcium (Bhutta, 2000; Gibson, Bailey, Gibbs, & Ferguson, 2010). Thus, complementary diets may have varying levels of benefit to the infant. An optimal diet for infant health is now considered to include a wide variety of foods from differing food groups, rather than a specialized diet of limited “infant” food. Foods rich in B vitamins, zinc, and iron should be offered alongside continued breastfeeding. Health authorities recommend family foods early in the complementary feeding period, including meat, fish, or eggs (Agostoni et al., 2008; Coulthard, Harris, & Emmett, 2009). While the onset of complementary feeding is somewhat constrained as to timing, the total length of the complementary feeding period is highly variable cross-culturally, as well as among primates (Sellen, 2009).

The persistence of breastfeeding in low-income and middle-income countries (LMICs) where complementary feeding may be insufficient or inappropriate, as a means of extra support, has led to widespread perception of breastfeeding as a cause of malnutrition and stunting. Breastfeeding by nutrient-deficient mothers is also sometimes cited as a cause of micronutrient deficiency in young children (cf. Walker et al., 2009; White et al., 2006), without further exploration of the wider implications of these deficiencies. For instance, is breastfeeding itself the cause of deficiency, or merely a means of transmitting maternal dietary deficiencies common to the culture which are also likely to be reflected in the complementary diet? Or are deficiencies a reflection of differential social access or behavior? These issues require some brief examination, considering published data on growth patterns and stunting among breastfed toddlers in low-income countries, and the known relationship between impaired immune function and nutrient deficiency (Scrimshaw, Taylor, & Gordon, 1968; Solomons, 2007).

Many studies in recent decades have examined the long-observed association between malnutrition and sustained breastfeeding in LMIC nations. While earlier studies suggested that breastfeeding may play a causal role in the development of malnutrition and consequent stunting (e.g. Brakohiapa et al., 1988; Thoren & Stintzing, 1988; Victora et al., 1984), more recent research suggests that the principle of reverse causality may often be in play. Mothers of children who are small for age, malnourished, and/or stunted have often been observed to opt for longer periods of breastfeeding to increase odds of infant survival (Caulfield, Bentley, & Ahmed, 1996; Fawzi, Herrera, Nestel, Amin, & Mohamed, 1998; Habicht, 2002; Jones et al., 2014; Kramer, Moodie, Dahhou, & Platt, 2011). In fact, while breastfed infants grow more slowly in the first year of life than non-breastfed infants, longer duration of breastfeeding has been associated with greater linear growth during the second year in several studies (Habicht, 2002; Onyango, Esrey, & Kramer, 1999; Simondon, Simondon, Costes, Delaunay, & Diallo, 2001). Providing that milk is not displaced by high-density, low-nutrient solid foods, breastfeeding may continue to form a significant supplementary source of calories and nutrients which does not impact negatively on growth throughout the complementary feeding period (Buckley, 2001; Kumwenda et al., 2016; Qadri & Hubaira, 2017). In most countries, the majority of postnatal growth restriction occurs during the period of complementary feeding, rather than the period of exclusive breastfeeding (Dewey, 2002; Dewey & Huffman, 2009; Victora, de Onis, Hallal, Blössner, & Shrimpton, 2010).

Moreover, recent research has suggested that although malnutrition may cause stunting, lower height should not be assumed to *in itself* signify malnutrition, as it may occur in children of varying socioeconomic and nutritional status; instead, height measurements should be considered alongside other indicators such as skin fold measurements (Scheffler et al., 2020). This point is particularly pertinent to bioarchaeology, where soft tissue measurements are unavailable, and length measurements in bone are often the only metrics available to assess growth and infer nutritional status in children. While the relationship between growth and malnutrition is complex and multifactorial, with intergenerational effects of fetal growth restriction themselves posing major challenges, the primary causes of stunting in infants of *normal* birthweight are believed to be inadequate quantities or quality of the complementary diet, poor sanitation, and the energetic burden of infection (Bhutta et al., 2013; White, Bégin, Kumapley, Murray, & Krasevec, 2017). Thus, for infants of normal birthweight, differential access to adequately nourishing complementary foods, together with overall health status, determines nutritional competence or deficiency, and subsequently influences normal or impaired growth (Anderson, Cornwall, Jack, & Gibson, 2008; Cetthakrikul et al., 2018; Dewey et al., 1992; Krebs et al., 2011).

Illness must also be considered as a complication for nutritional status. Infection, for instance, may cause sickness-induced anorexia (Ayres, 2013), which may exacerbate pre-existing malnutrition arising from an inadequate complementary diet. Malnutrition itself also impairs immune response, leading to a risk of entering a synergistic and chronic malnutrition-infection cycle frequently observed in epidemiology (Guerrant, Oriá, Moore, Oriá, & Lima, 2008; Solomons, 2007). Pathogenic infection of the gut damages the mucosal epithelium, decreasing defensive barrier mechanisms and increasing risks of nutrient malabsorption and subsequent malnutrition (Guerrant, DeBoer, Moore, Scharf, & Lima, 2013). In addition to preventing infection and reducing severity of illness, breastmilk is responsible for maintenance and repair of damaged intestinal epithelium through its use of components such as growth factors and nucleotides (Dvorak, 2010). Effects of infection on appetite, too, may be ameliorated by breastfeeding. Factors in human milk have been shown to suppress increases in concentration of leptin, a hormone that inhibits hunger, allowing breastfeeding to continue uninterrupted as an exceptional source of electrolytes, nutrients, protective bioactive

elements, and fluids (Brown, Stallings, de Kanashiro, Lopez de Romaña, & Black, 1990; López-Alarcón, García-Zuñiga, Del Prado, & Garza, 2004; López-Alarcón, Garza, del Prado, García-Zúñiga, & Barbosa, 2008). These unique mechanisms may go some way to interrupting the infection-malnutrition cycle in children during the complementary feeding period. Children who continue to be breastfed alongside complementary foods commonly experience fewer and less severe health impacts from diarrheal illness than non-breastfed children, even beyond infancy (Betrán, de Onis, Lauer, & Villar, 2001; Budhathoki, Bhattachan, Yadav, Upadhyaya, & Pokharel, 2016; Strand et al., 2012; Wright, Mendez, Bentley, & Adair, 2017).

Accordingly, Suzanne Filteau has asserted that

> ...complementary foods are not themselves the major problem, and it is the active role of breast milk which is primary for maintaining gut integrity. Thus, although we may have overestimated the damage caused by weaning foods, we may have underestimated the gut protective effects of breast milk (Filteau, 2000: 567).

To be clear, none of this is to suggest that breastfed children do not become ill or malnourished during the complementary feeding phase, particularly in LMIC settings. It is evident that they do, and that children raised in high-pathogen and low-resource environments suffer from higher prevalence of illness than those raised in lower-risk settings. Nonetheless, based on robust evidence, breastfeeding in line with current recommendations – initiation at birth, exclusivity to six months, and continued breastfeeding alongside adequately nourishing complementary foods – has been suggested as a powerful and critical means of promoting child health equity worldwide (Perez-Escamilla et al., 2018; Roberts, Carnahan, & Gakidou, 2013).

However, it is also clear that children continue to benefit from the buffering immunological and nutritional support of supplementary breastfeeding alongside complementary foods, where increasing antigenic challenges would otherwise outstrip their developmental abilities to mount an adequate response. The difference between the health of an exclusively breastfed child at 5 months of age and a child being fed complementary foods should not be assumed to be a difference in the quality of milk that they are fed, but a difference in the antigenic challenges presented. Nor should we assume a zero-sum relationship between complementary feeding and breastfeeding. Clearly, breastfed children cope better with the pathogenic load presented by introduced foods than those of a comparable level of immunological competence without such support. Thus, the most perilous period for breastfed children may not occur when solid foods are first introduced, as previously assumed. Data reviewed in this paper show that immunological and nutritive forces are still in operation and adapting to changing needs during the complementary feeding period. Instead, as full immunological competence is rarely achieved before breastfeeding comes to an end, the greatest dangers for children in high-pathogen settings may occur following cessation of breastfeeding, when they cease to be immunologically buffered.

Filteau's statement regarding overestimation of microbiological risk in complementary feeding is accurate. However, in terms of bioarchaeological interpretation, complementary foods are indeed a problem. Lack of *access* to an adequate or appropriate complementary diet is far more likely to be implicated in past instances of child malnutrition than is typically remarked upon in bioarchaeology, where inappropriately "prolonged" or maternally deficient exclusive breastfeeding is more frequently named as a contributor to undernutrition or observed growth deficits. To some extent, a greater emphasis on breastfeeding than on complementary foods may be a function of accessibility. While we may be able to infer

continued breastfeeding from measures such as stable isotope data, the problem of equifinality prevents us from identifying precisely which foods were being consumed by young children in the same data. Similarly, we can only ever recover ratios, not absolute quantities of foodstuffs. The resulting emphasis is unfortunate, as it runs directly counter to extant data on child health. In this sense, the weanling's dilemma in archaeology has become somewhat warped. The dilemma for young children in LMIC environments is not whether to risk malnutrition through breastfeeding, or loss of immune protections through complementary feeding. Rather, it is far more often how to avoid becoming malnourished during complementary feeding, and how to cope once breastfeeding ceases.

Here, some nuance is required. Most data on global child nutrition, and particularly long-term breastfeeding, are derived from LMIC environments in the Global South, where ongoing legacies of political, cultural, and economic colonization are continuing to impact on child health (Gaard, 2013; Raschke & Cheema, 2008). Where skeletal indicators of nutritional deficiency are observed in concert with similar contextual evidence of sociopolitical or environmental marginality in archaeological populations, or where contextual information suggests culturally restrictive child diet, it may be valid to focus on the deleterious inadequacies of complementary diet. However, while nearly all past contexts can be assumed to be unhygienic by WEIRD standards, it is highly unlikely that child food poverty was a universal feature of past societies, or that breastfeeding of otherwise well-nourished children played an insignificant role in buffering children from the worst effects of antigenic challenge. In this sense, it is possible that unnuanced application of the weanling's dilemma in bioarchaeology paints a picture of past child health that is unnecessarily bleak, and in doing so underestimates the buffering impacts of breastfeeding on child health during complementary feeding.

Challenging Negative Assumptions: A Case Study From Neolithic Spain

In order to illustrate the ways in which negative perceptions of complementary feeding and continued breastfeeding might influence conclusions in research, and to constructively demonstrate how applying a different interpretative lens might offer a more nuanced picture of past childhood health and nutrition, we sought a case study from the published literature. A study of late Neolithic (3500–2900 cal. BC) childhood diet at Alto de la Huesera, Spain by Fernández-Crespo et al. (2018) analyzed juvenile bone (n=17) alongside incrementally-sampled permanent first (M1) and second molar (M2) dentine from adults (n=7) to characterize early life dietary transitions in a life history approach. Due to concerns with the applicability or comparison value of juvenile bone collagen for assessing breastfeeding patterns (Beaumont et al., 2018), we will only revisit the latter dataset here. Dentine data represented approximately the first ten years of life (for M1s) and ages 2 to 16 (for M2s) (Al Qahtani, Hector, & Liversidge, 2010; Beaumont & Montgomery, 2015), providing good coverage of crucial developmental windows. Evidence of traumatic injuries at the site, suggesting interpersonal violence and a "warlike society", led the authors to investigate possible sex-based differences in early childhood diet which might stem from greater parental investment in males (Fernández-Crespo et al., 2018: 543).

Previous analyses of adult bone collagen at the site had suggested a diet dependent on C_3 (temperate) plants and terrestrial animal sources of protein (Fernández-Crespo & Schulting, 2017). Evidence of micronutrient deficiency was also present in the wider population (n=56), with three cases of possible rickets and eleven cases of cribra orbitalia present. Indications of generalized childhood stress were also present, albeit at low prevalence, with a minimum of 5 individuals exhibiting enamel hypoplasia. These findings were used to contextualize interpretation of the isotope data. From these data, the authors

inferred delayed introduction of solids occurring in the second year of life, with girls being exclusively breastfed for longer than boys. This was hypothesized to be due to preferential provisioning of male offspring with complementary foods in an environment of food scarcity, or to the need to separate male children from their mother earlier to ensure a suitable warrior masculinity. The presence of stress markers was interpreted as being linked to breastfeeding practices, suggesting that exclusive breastfeeding beyond six months and undernutrition may have been contributors.

A reappraisal of the data provides a slightly different picture. Fernández-Crespo et al. (2018) state that in most of the study individuals, dentine formed prior to one year of age was lost to dental attrition. Furthermore, even with the most sophisticated incremental sampling methods, time averaging will inevitably occur as multiple incremental boundaries are crossed in order to obtain enough tissue to meet minimum sample sizes. It is also not unlikely that generally, complementary foods may be introduced well in advance of a detectable $\delta^{15}N$ shift of significant magnitude, especially early in the complementary feeding process where transition is gradual, and amounts of non-breastmilk foods are necessarily small (Dewey, 2013; Millard, 2000). Fuller et al. (2006a) previously suggested that shifts in $\delta^{13}C$ may provide the most sensitive measure of the introduction of complementary foods, while $\delta^{15}N$ may better track human milk intake. It is impossible to infer dietary inputs from an absence of analytical data in the target age range. However, in all but one individual (LHUE34) in the Alto de la Huesera incremental data, $\delta^{13}C$ values are dropping towards, or are actually on a par with, adult values from one year of age in both females (Figure 1) and males (Figure 2). Consequently, and with such a small sample size, it is difficult to share the authors' certainty that complementary foods were *not* introduced in the first year of life for most individuals, or that provision of complementary foods was gendered. In this case, we have an absence of evidence, rather than evidence of absence, per se.

In terms of the perceived gendered dimension of breastfeeding practices in the Alto de la Huesera incremental sample, the study did produce some interesting patterns. In general, males did show an earlier and steeper decline in $\delta^{15}N$ values (Figure 3), which might be interpreted as indicating an earlier and more rapid cessation of breastfeeding. However, two main issues make a simple reading of the data as gendered problematic. Firstly, within the male sample, there is variation in slope, with LHUE2i showing a much more gradual decline than LHUE17c or LHUE19c. Furthermore, LHUE53 plots with and exhibits a similar pattern in $\delta^{15}N$ decline to the females in the sample. In this regard, there is more variability in pattern within the male sample than between the male and female samples. With these considerations, and the small sample size from which to draw conclusions, it may be worth considering differential social status as another factor which may mediate infant care and feeding strategies, alongside gender and environment.

Nutritional stress in the early childhood data which would imply malnourishment, or deleterious reliance on exclusive breastfeeding, is also not apparent. The authors themselves note that "breastmilk only provides as much as a half of a child's energy needs between the ages of 6 and 12 months, and up to one third of energy needs between 12 and 24 months" (Fernández-Crespo et al., 2018: 548). While micronutrient malnutrition is unlikely to produce measurable changes in $\delta^{15}N$ or $\delta^{13}C$ values, calorie and protein malnutrition would also result from exclusive breastfeeding for a year or more. Undernutrition in calories and/or protein would cause the body to catabolize (break down) its own fat and muscle tissues to meet maintenance demands, resulting in weight loss and a characteristic pattern of concurrently rising $\delta^{15}N$ and falling $\delta^{13}C$ which is typically visible in the isotopic data of individuals suffering from malnutrition (Beaumont & Montgomery, 2016; Mekota, Grupe, Ufer, & Cuntz, 2006). Such patterns are not evident in the Alto de la Huesera M1 data.

Instead, instances of the *opposite* trend, anabolic change – an increase in body mass relating to weight gain or growth – are observable as rising $\delta^{13}C$ and dipping $\delta^{15}N$ in the profiles of LHUE34, LHUE36, LHUE52, LHUE2i, LHUE17c, and LHUE19c. Isotopic effects of anabolic changes have previously been observed in observational studies of pregnancy and recovery from anorexia nervosa (Fuller et al., 2004; Reissland et al., 2020) Based on age at occurrence, these anabolic changes most likely relate to the mid-growth spurt, which is a period of brief but intense growth seen in most children during middle childhood (Campbell, 2011; Hermanussen, 2016). Growth is saltatory, and dependent on adequate nutrition, which suggests that the individuals in this sample exhibited good nutritional status and evidence of normal growth intervals.

Isotopic evidence for normal growth and dietary patterns is not impossible, or even difficult, to reconcile with the presence of rickets and cribra orbitalia at Alto de la Huesera. While Fernández-Crespo and colleagues recognized that cribra orbitalia may relate to early childhood anemias with non-dietary etiologies, such as parasitic infection (Gowland & Western, 2012; Walker et al., 2009), the presence of rickets in three juvenile individuals was presumed to relate to dietary restriction and exclusive breastfeeding beyond six months of age. Moreover, this was extrapolated as supporting a trend of exclusive breastfeeding in the population more broadly. Aside from the lack of isotopic evidence in this sample to support a delayed introduction of complementary foods, dietary restriction is also unlikely to account for the presence of rickets in this population.

Rickets may result from a range of conditions, but the most frequent causes of nutritional rickets are deficiencies of calcium or Vitamin D, with rickets being most commonly viewed as a proxy for the latter in bioarchaeology (Snoddy, Buckley, & Halcrow, 2016). Vitamin D in humans is primarily synthesized by the skin via exposure to UVB rays in sunlight, rather than consumed through diet, as few foods contain significant amounts of Vitamin D (World Health Organization, 2019). While suboptimal Vitamin D status is not unknown in Spain, where it has been observed in modern populations, this has typically been found to relate to sun avoidance behaviors, as UVB is present in sufficient quantities at these latitudes (Navarro Valverde & Quesada Gómez, 2014). As the cases of rickets were found at Alto de la Huesera in deceased juveniles, rather than being present as healed rickets in individuals surviving to adulthood, it is plausible that these children were chronically ill, and thus spent less time outdoors than their peers. Another, rarer, possibility to explore would involve the possibility that the children were related and had in common a heritable inborn disorder of Vitamin D metabolism which rendered them incapable of synthesizing Vitamin D from sunlight (Feldman & J Malloy, 2014; Surender, Kochar, Ahmad, & Kapoor, 2014). Regardless, these are exceptional cases in which the osteological paradox would apply and should not be generalizable to broader societal behaviors without further evidence to suggest the representative nature of such cases. In all respects, as researchers we must exercise caution when interpreting data, ensuring that our conclusions are evidence-based and informed by multidisciplinary pools of knowledge.

In many respects, the paper by Fernández-Crespo and colleagues is a typical example of twenty-first century paleodietary scholarship. Their biogeochemical methodology is sound and current, and their conclusions generally orthodox. It is not our goal here to denigrate our worthy peers and fellow scholars. Rather, it is the very orthodoxy of such conclusions which we wish to critique, largely derived from unconscious cultural beliefs and outdated scientific premises. For instance, in reference to complementary feeding it is claimed that "the declining immunological benefit of breastmilk and the increasing exposure to environmental pathogens are often associated with an increased incidence of illness, particularly intestinal and immune system dysfunctions" (Fernández-Crespo et al., 2018: 543). This draws heavily from an understanding of immunological benefits which are limited in scope by passive

protections and duration by the introduction of complementary foods. This claim is interestingly *not* supported by the source they cite, which instead remarks that "in many nonindustrialized populations in which traditional breastfeeding practices are still observed, weaning foods are introduced around 3 months, but infants may continue to nurse well past the first year of life…ongoing nursing would provide infants with continued access to beneficial probiotic, prebiotic, and antimicrobial factors in milk" (Martin & Sela, 2013: 246). Instead, as with many other papers, this perspective is implicitly informed by the older immunological viewpoints expressed in the influential paleodietary paper by Katzenberg et al. (1996).

Similarly, concerns associating "prolonged" breastfeeding with nutritional deprivation are present in the paper, as the authors comment that "…weaning seems to be an extended process in Alto de la Huesera. This could also be related with problems with food availability and supply during an extended period of even low-level conflict, due to perceived danger and insecurity" (Fernández-Crespo et al., 2018: 548). Description of a gradual transition lasting several years, normal in many human societies, as "extended" and implying a crisis, reveals assumptions drawn from a WEIRD frame of reference, where a rapid cessation of breastfeeding is normative. Negative inferences regarding the role of breastfeeding in child health and nutrition are subtly infused throughout the paper, which is fairly representative of research in the discipline.

However, a more neutral alternative reading of the isotopic evidence, which draws equally from the pre-existing osteological data and current lactation science, is possible. The lack of evidence for nutritional stress in the isotopic data, though drawn from a small dataset, could have suggested that the length of the complementary feeding period was an intentional and successful general strategy for child survival in a hostile environment which is borne out in the adult status of the remains. Evidence for anabolic activity in middle childhood, compatible with an interpretation of the mid-growth spurt as it appears in modern children, might offer evidence that these individuals were well-nourished. Furthermore, where surviving adult individuals have evidence of nonspecific childhood skeletal stress markers, such as cribra orbitalia or enamel hypoplasia, this may suggest that the adaptive importance of breastfeeding also had a specific role in supporting the survival of offspring through environmental stressors and childhood infections during a vulnerable period. Viewed as an asset, rather than a liability, evidence for sustained breastfeeding alongside complementary foods may provide key insights into social and biological factors which mediate resilience.

How Do We Move Forward?

Patricia Stuart-Macadam once stated: "Breast milk is not a magic potion, not a panacea for all human ills. It is a vital, dynamic substance that can transmit both beneficial (such as immunoglobulins and nutrients) and detrimental (such as nicotine and alcohol) substances to the infant" (Stuart-Macadam, 1995: 27). This is a balanced assessment of the essential nature of human milk. However, beyond viewing human milk as a substance, it is important to integrate an understanding of breastfeeding as a dynamic, embodied process into future interpretative frameworks. Highly evolved as an adaptive nexus between mother and infant during a crucial priming period, breastfeeding is a cooperative effort in which children play an active and decisive role. Human milk provides offspring with nutrition and shared immunity, shielding them from environmental insults and excessive growth-impairing demands. Nonetheless, breastfeeding is presently undervalued within bioarchaeology in the range of bioactive elements in milk and its adaptability to the needs of the child throughout lactation. Finally, it is important to emphasize that when studying past breastfeeding patterns in reference to early life health, we are addressing more than abstract biological systems (or impacts on population health, demography, fertility, or economics). Rather than seeking

culturally prescribed norms alone, we are concerning ourselves with a highly variable dance of negotiation, as individualized and social as the relationships and circumstances involved.

Within the fields of paleodietary studies and bioarchaeology, a pervasive interpretive underestimation of the protective role of breastfeeding has occurred. Engagement with evidence for the complex adaptive system represented by the breastfeeding dyad, and its long-term role in supporting immune defense, metabolic function, nutrition, and growth will be essential to the continuing development of studies engaging with past childhood health. To do so, a shift in bioarchaeology is needed, whereby the discipline engages more fully with external disciplines and researchers. Bioarchaeologists need to make use of *all* relevant sources of data to develop interpretative frameworks and collaborative networks that can keep pace with developing evidence bases. Familiarity with a wide range of data can also provide an empirical challenge to unconsciously-held cultural beliefs and influences.

In moving forward, we would firstly encourage bioarchaeologists and paleodiet researchers to access and make use of current and emerging research on the biological impacts of breastfeeding, in both breadth and depth. In addition to global nutrition research, lactation immunology and microbiome research are exciting and rapidly evolving resources with great relevance for paleodietary research. However, as these are complex areas of expertise, frequent consultation of the literature and collaboration with researchers in those areas is also advisable. Crosstalk and collaboration among anthropologists are desirable in any case, as we can offer valuable insights to each other which are not obvious from within our subdisciplines, including ensuring that we understand and accurately represent sources from outside of our own fields. Similarly, an appreciation of the range of cultural and temporal variation in infant feeding practices is essential to inform assumptions regarding human behavioral norms. Finally, bioarchaeologists' interpretations of their data need to be based on this broader evidence-based understanding of the cultural and bio-behavioral dynamics of breastfeeding, and five key points have emerged from our consideration of this:

1. We need to be aware that our own cultural backgrounds may cause us to make assumptions about breastfeeding that are not applicable to the past.
2. In particular, the idea that sustained breastfeeding is inevitably deleterious needs to be discarded in favor of a contextual assessment of its effects on both mother and child.
3. As we have argued here, if the concept of the weanling's dilemma has any applicability, it is likely to be at the cessation of breastfeeding, rather than the onset of complementary feeding.
4. The terminology we use needs to be precise. We recommend avoiding the unqualified use of the word "weaning", which has often been used imprecisely and can obfuscate meaning, leading to poorly framed arguments and misunderstandings.
5. In the light of the points above, we suggest active and mindful engagement with past and present literature within bioarchaeology and beyond, in relevant cognate disciplines. We should also consider revisiting past datasets, where conclusions may have been based on faulty premises, and reconsideration may yield new insights.

Application of these ideas will improve the quality of our research networks and outputs. To paraphrase Bob Dylan: the data, they are a-changin'. Within paleodiet studies, the complexity of our methods and data are evolving rapidly, and our interpretative paradigms and knowledge bases need to move along with them.

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Table 1 Selected bioactive factors in human milk

Factor	Function	Level	References
Antibodies			
Secretory IgA (sIgA)	Neutralize pathogens	Mucosal	Lönnerdal, 2016
IgG	Immunomodulatory	Systemic	Gao et al., 2012
IgM	Neutralize pathogens; activate complement system	Mucosal	Hassiotou et al., 2013
Maternal cells			
Leukocytes	Active host defense; immune maturation	Systemic	Järvinen & Suomalainen, 2002
T cells	B cell maturation; pathogen cytoxicity	Systemic	Cabinian et al., 2016
B cells	Secrete antibodies	Systemic	Newburg, 2005
Macrophages	Phagocytose pathogens; activate T cells	Systemic	Jakaitis & Denning, 2014, Riskin et al., 2012
Multipotent stem cells	Immune/tissue development	Systemic	Patki et al., 2010
Microbes	Anti-inflammatory; immunomodulatory; create anti-pathogenic environment; metabolic programming	Mucosal	McGuire & McGuire, 2015
Carbohydrates			
Oligosaccharides (HMOs)	Prebiotic; neutralize pathogens; anti-inflammatory	Systemic	Bode, 2012, Kulinich & Liu, 2016
Proteins and peptides			
β-casein	Enhance innate immune response, gut maturation	Systemic	Kitazawa et al., 2007
κ-casein	Prebiotic; neutralize pathogens	Mucosal	Wada & Lönnerdal, 2014
Human α-lactalbumin made lethal to tumor cells (HAMLET)	Antimicrobial; anti-carcinogenic	Systemic	Hakansson et al., 2011
Mucins	Antimicrobial; immunoregulatory	Mucosal	Liu & Newburg, 2013

Factor	Function	Level	References
Lactoferrin	Antimicrobial; withholds iron from pathogens; immune maturation and modulation	Systemic	Siqueiros-Cendón et al., 2014; Lönnerdal, 2017
Haptocorrin	Antimicrobial; withholds B_{12} from pathogens	Mucosal	Adkins & Lönnerdal, 2003
Osteopontin	Immunoregulatory; anti-inflammatory	Systemic	Nagatomo et al., 2004
Enzymes			
Lactoperoxidase	Antibacterial	Mucosal	Wijkstrom-Frei et al., 2003
Lysozyme	Antibacterial; anti-inflammatory	Mucosal	Lönnerdal, 2010
Lipids			
Fatty acids	Inhibit proliferation of microbes; immune and neurological maturation; T cell regulation	Systemic	Kelsey et al., 2006, Hadley et al., 2016
Hormones	Immunomodulation; tissue maturation; metabolic regulation	Systemic	Savino et al., 2013, Semba & Juul, 2002
Cytokines	Immunomodulation; immune maturation	Systemic	Garofalo, 2010, Oddy & Rosales, 2010

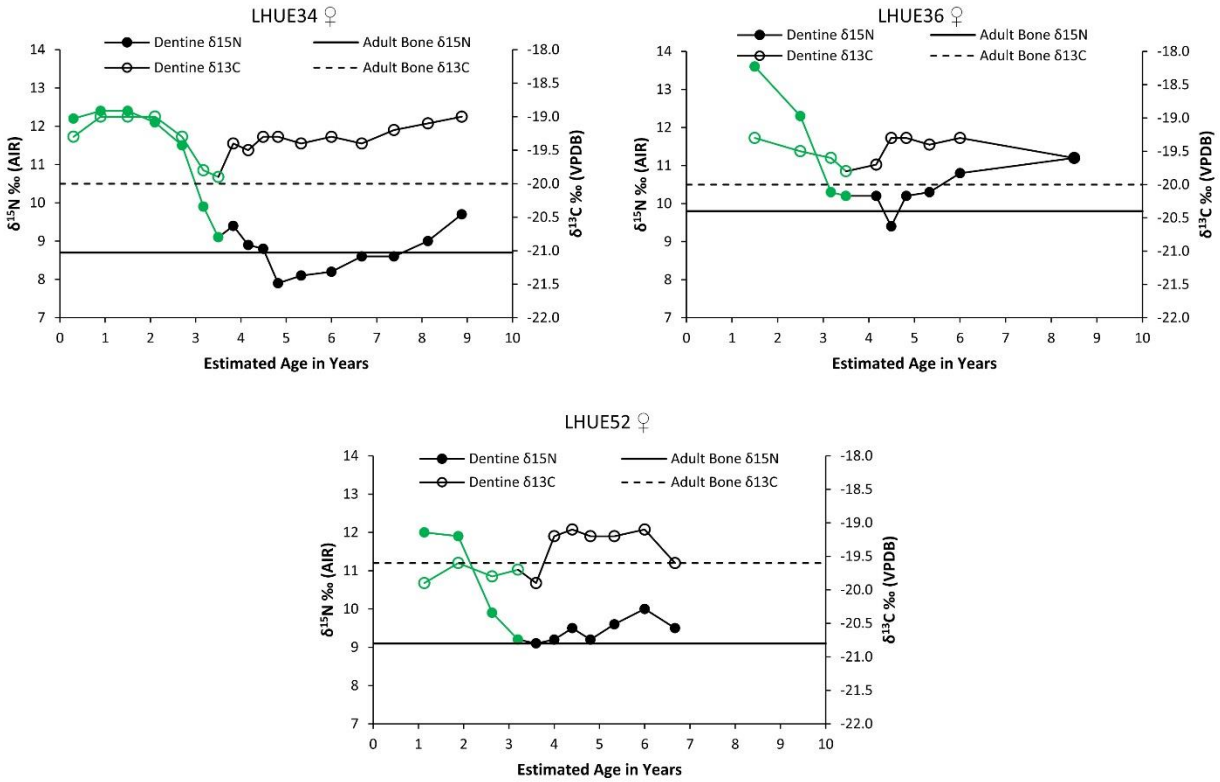

Figure 1. $\delta^{15}N$ and $\delta^{13}C$ M1 profile data for females at Alto de la Huesera (Fernández-Crespo et al., 2018) compared to adult bone values (Fernández-Crespo and Schulting, 2017), with breastfeeding period highlighted in green. This is a de novo figure of data drawn from previously published supplementary information.

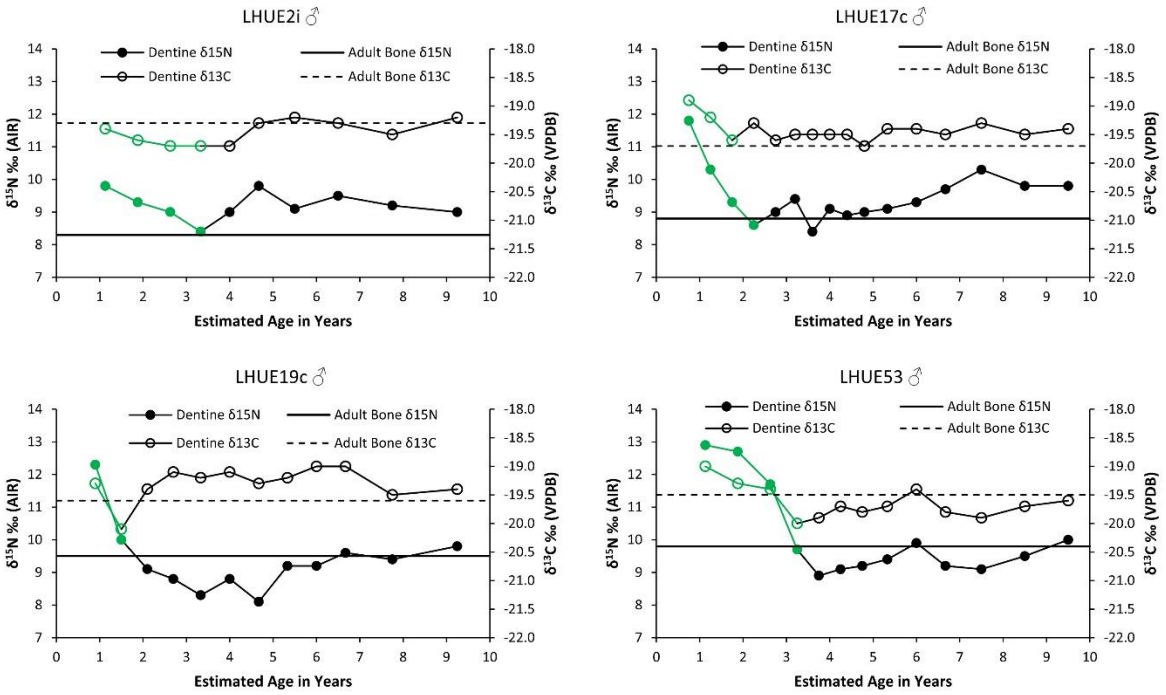

Figure 2. $\delta^{15}N$ and $\delta^{13}C$ M1 profile data for males at Alto de la Huesera (Fernández-Crespo et al., 2018) compared to adult bone values (Fernández-Crespo and Schulting, 2017), with breastfeeding period highlighted in green. This is a de novo figure of data drawn from previously published supplementary information.

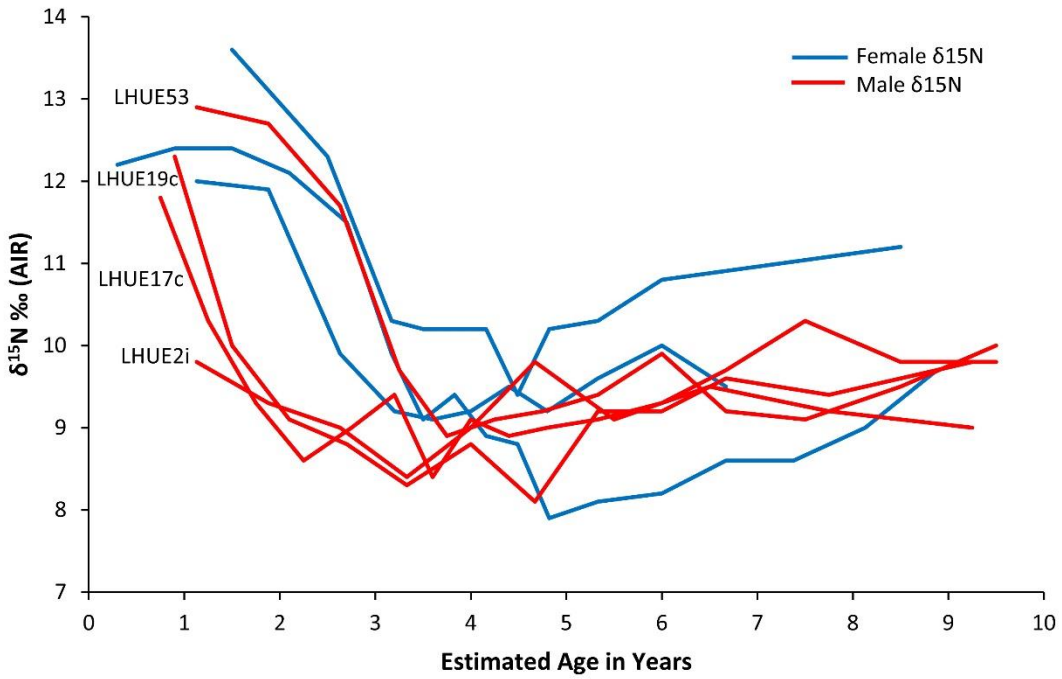

Figure 3. $\delta^{15}N$ M1 profile data by sex at Alto de la Huesera (Fernández-Crespo et al., 2018), with male (red) profiles labelled by individual profile. This is a de novo figure of data drawn from previously published supplementary information.