Chapter X: Modeling developmental plasticity in human growth: buffering the past or predicting the future?

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Abstract

Substantial variation in adult body size between human populations is widely assumed in part to represent adaptation to local ecological conditions. Developmental plasticity contributes to such variability, however there is debate regarding how this early-life process can produce adaptation when environments change within the lifespan. We developed a simple mathematical simulation model, testing how human fetuses could tailor their growth to ecological conditions without being over-sensitive, and hence prone to extremes of growth. Data on Indian rainfall (1871-2002) were used as an index of ecological conditions. The simulation model allowed comparison of different strategies for processing these time-series data regarding (a) the toleration of short-term ecological variability and (b) the prediction of conditions in adulthood. We showed that ecological information processing is favored in environments prone to long-term ecological trends. Once this strategy is adopted, resistance to short-term ecological perturbations can be achieved either by lengthening the duration of developmental plasticity, or by accumulating multi-generational influences. A multi-generational strategy successfully dampens the transmission of the effects of ecological shocks to future generations, but it does not predict or enable offspring to respond to longer-term conditions. However, this strategy does allow fetal growth to be tailored to the likely supply of nutrition from the mother in the period after birth, when extrinsic mortality risk is high. Our model has implications for public health policies aimed at addressing chronic malnutrition.

Keywords: developmental plasticity, growth, adaptation, human ecology

X.1 Introduction

The concept of adaptation assumes that organisms optimize their evolutionary fitness by improving their ability to survive and breed in a given environment. Adaptive variation in body size is predicted to emerge through cumulative trade-offs between the life history functions of survival, growth and reproduction, as shaped by diverse ecological factors (Harvey et al., 1987; Hill, 1993). In humans, variability in adult size has been associated with factors such as the thermal environment, energy supply and mortality risk (Katzmarzyk and Leonard, 1998; Walker et al., 2006). A portion of this variability appears to have occurred as a result of natural selection acting directly on genetic variability, since over 200 genes have now been associated with adult height in humans (Lango-Allen et al., 2010), and the trait has high heritability (Silventoinen et al., 2003; though see Wells and Stock 2011).

In addition to genotype, phenotypic plasticity represents an alternative means whereby organisms can respond to ecological stresses (West-Eberhard, 2003). It might appear intuitive that phenotypic plasticity should favor adaptation to ecological conditions – however, not all plasticity results in greater fitness (Via et al., 1995; Ellison and Jasienska 2007). For human body size, much of the variability in adult phenotype derives from growth variability early in the life course. Growth becomes increasingly canalized from early childhood on (Bogin, 1999; Mei et al., 2004; Smith et al., 1976). This pattern, in which plasticity in many traits is greatest in early life, is widely prevalent across species (Bateson, 2001; McCance, 1962; Widdowson and McCance, 1960). Such 'developmental plasticity' is certainly one way in which phenotypic variability is shaped by ecological stresses. In humans, however, the primary period of plasticity occurs two

decades prior to exposure to the adult environment, wherein many selective pressures relevant to reproductive fitness must act. This raises questions regarding the extent to which developmental plasticity in our species is indeed adaptive throughout the entire life-course or under all ecological circumstances.

That human growth variability has an adaptive component over the *short*-term is well established. In general, higher body weight at birth and during infancy is associated with greater survival early in life (Hogue et al., 1987; Kow et al., 1991; Victora et al., 2001), when extrinsic mortality risk is greatest. When nutritional supply is constrained, however, offspring grow slowly, and appear to prioritize growth and development of some organs or body components at the cost of others (Hales and Barker 1992; Latini et al., 2004; Pomeroy et al., 2012).

The notion that early growth variability has *long*-term adaptive value is more controversial. If ecological stresses encountered in early life persist into later life, then developmental plasticity might promote fitness of the organism in its adult environment. For example, the thermal environment tends to be relatively consistent across broad global regions, hence heat and cold stress early in life might induce beneficial adjustments in body size and proportions. Consistent with that hypothesis, ecogeographical analyses have demonstrated correlations of both adult phenotype and birth weight with heat stress (Roberts, 1953; Katzmarzyk and Leonard, 1998; Wells and Cole, 2002; Wells 2012a), suggesting that human adaptation to the thermal environment begins *in utero*.

In volatile or unpredictable environments, however, deriving adult adaptation through early-life plasticity is inherently challenging. Palaeo-climate evidence indicates that hominin evolution took place in increasingly stochastic environments (Bonnefille et al., 2004; Lisiecki and Raymo, 2005; Potts, 2012a; b; Trauth et al., 2005). Long-term 'Milankovitch cycles' drive climate change over tens of thousands of years (Glantz, 2001). Shorter-term climate cycles are also evident in the hominin palaeo-climate record (Wang et al., 2008), including some that are analogous to contemporary El Niño Southern Oscillation (ENSO) cycles (Hughen et al., 1999). These climate cycles, in turn, can be assumed to have introduced shorter-term ecological variability. Although phenotypic plasticity may potentially aid adaptation in such stochastic environments, developmental plasticity has a low degree of reversibility (Piersma and Drent, 2003), and any adaptive benefits might not extend into adulthood.

This potential for disconnect between early-life plasticity and later-life adaptation is likely to have been exacerbated in recent human evolution by a substantial lengthening of the developmental period (Bogin and Smith, 1996) which, paradoxically, may itself have been favored by stochastic environments (Wells, 2012b). Whereas other female apes achieve reproductive maturity within a decade of birth (Galdikas and Wood, 1990; Robson and Wood, 2008), humans require around two decades to reach the same state. In volatile environments, this extended growth period decreases the likelihood that early plasticity will generate traits well-suited to the ecological conditions encountered in adulthood. How then can developmental plasticity actually allow beneficial adaptation to the environment?

Whilst ecological stresses may be evaluated in terms of direct, material environmental effects on growth, they may also be considered as a source of 'information' about the quality of the environment with the potential to have more indirect, sustained effects (Bateson, 2001). We can reframe the dilemma concerning timing of adaptive influences on developmental plasticity as follows: How might information received by organisms early in life be translated or processed in terms of adaptive growth patterns?

X.2 Developmental plasticity as information processing

Several different models of developmental plasticity as information processing have been proposed previously. A general approach was offered by Bateson (2001); in this. 'weather forecast' model, the developing organism receives cues of impending environmental conditions, and selects an appropriate developmental trajectory accordingly. Since physiological plasticity cannot be maintained indefinitely, a specific strategy must be selected early in life during a critical window of development. An accurate weather forecast is assumed to enable an appropriate future strategy, whereas an inaccurate forecast results in the organism being poorly prepared for its long-term environment. Key questions arising from this perspective are, first, what specific cues about the environment are obtained, and second, what broader ecological parameters do those cues index?

This 'forecasting' framework has been extended by Gluckman and Hanson (2004a; 2004b) in the form of the 'predictive adaptive response' (PAR) hypothesis. This model assumes that developing offspring receive cues during pregnancy about the state of the environment and use them to predict the adult environment in which reproduction is

likely to take place (Gluckman and Hanson, 2004a; 2004b; Gluckman et al., 2007). For example, offspring experiencing famine in early life are assumed to prepare for persisting famine in adulthood through enhancing traits such as insulin resistance and central adiposity. The challenge of this approach for a long-lived species like humans is that predictions about the environment must be accurate for several decades in the future and remain accurate, given that reproduction does not even begin until late in the second decade after birth.

This PAR hypothesis has been extensively criticized on several grounds, all related to the idea that such long-term forecasting is implausible (Jones, 2005; Bogin et al., 2007; Rickard and Lummaa, 2007; Wells, 2007a; 2010; 2012c). First, spectral analyses of simulated or historically stochastic environments fail to support the hypothesis that current or recent-past conditions can predict future conditions (Wells 2007a; Baig et al., 2011). Second, mortality is highest in human foragers in early life, raising questions as to how 'long-term anticipatory adaptation' could develop in traits already strongly exposed to selection earlier in the life course (Wells, 2007a). Third, empirical data often contradict the predictions of the PAR hypothesis (Wells, 2012c): for example, Gambians under seasonal energy scarcity do not develop insulin resistance following low birth weight (Moore et al., 2001). An alternative 'silver spoon' hypothesis predicts that offspring receiving more early-life investment have higher reproductive fitness in all types of adult environments (Monaghan, 2008). This hypothesis is supported in the comparative literature for a variety of vertebrate animal species, including humans (Monaghan, 2008; Hayward et al., 2013).

An alternative 'maternal capital hypothesis' emphasizes that the information processed by offspring during placental nutrition and lactation derives from the maternal phenotype, rather than directly from the external environment (Wells, 2003; 2010; 2012c). Notably, human birth weight is only moderately depressed during maternal famine, and only moderately increased following maternal supplementation, indicating that maternal physiology buffers the fetus from short-term fluctuations (Wells, 2003). Exposure of the fetus to maternal phenotype, representing the cumulative effect of the nutritional environment experienced during development (Emauel et al., 2004; Hyppönen et al., 2004; Jasienska 2009), as well as any previous reproductive experience for the mother, means that "short-term fluctuations smoothed out to provide a more reliable rating of environmental quality" (Wells 2003). In this approach, adaptation through developmental plasticity is considered to be not to long-term future conditions, but to 'maternal capital' (Wells, 2003; 2010; 2012c). This approach also emphasizes that offspring plasticity makes possible 'maternal effects' that benefit maternal as well as offspring fitness (Wells 2003; 2007b).

Elements of both the PAR hypothesis and maternal buffering have been presented by Kuzawa (2005) in his model of 'inter-generational inertia'. As with the maternal capital hypothesis, Kuzawa argued that maternal phenotype buffers the offspring from short-term ecological perturbations, and provides a smoothed signal of ecological conditions deriving from matrilineal experience. As in the PAR hypothesis, however, Kuzawa assumes that this smoothed signal early in life aids the long-term prediction of ecological conditions, by providing "a 'best guess' of conditions likely to be experienced in the future" (Kuzawa and Bragg, 2012).

These three models, therefore, while they all treat developmental plasticity as adaptive, have significant differences (**Box 1**). One difference involves the time-scale over which the information is acquired. Another difference concerns the stage of the life-course at which the adaptive response is assumed to be targeted. To date, debate over these contrasting approaches has been conducted through verbal arguments, with little systematic testing of competing hypotheses.

We aimed to develop a simple mathematical model that enables the evaluation of different strategies by which offspring can obtain information early in life on environmental conditions relevant to fitness. We addressed three different types of ecological variability, as depicted schematically in **Figure 1**. First, the environment may be subject to clear annual cycles, with peaks and troughs in ecological productivity. Second, the environment may be subject to systematic trends, such that ecological productivity may rise or fall over lengthy time periods, as might occur through larger climate trends. Third, the environment may be subject to irregular, unpredictable 'extreme events', which superimpose major perturbations on other, more consistent patterns. Each of these three types of variability can be detected in the segment of the climate record relevant to human evolution, as well as in recent decades. For example, India experiences annual climate cycles, local systematic trends in rainfall, and irregular ENSO events that provoke monsoon failure (Glantz, 2001; Guhathakurta and Rajeevan, 2007).

Figure 1 near here

To operationalize this approach, we used rainfall data from India as an index of ecological productivity, and considered the kind of information that could be extracted from this record and processed adaptively by humans early in life, during the period of greatest developmental plasticity. We first considered the conditions under which it pays offspring to process information at all; then, having demonstrated that information processing can indeed be adaptive, we considered how different kinds of ecological variability can be adaptively translated and processed.

X.3 The rationale of the model

Data on monthly rainfall (R) for the period January 1871 to December 2002 were obtained from the IRI/LDEO Climate Data Library (http://iridl.ldeo.columbia.edu), for the region of India designated 'core monsoon', located at 76° E, 22.5° N. The typical pattern of variability is shown in **Figure 2**, illustrating both annual variability and the 1900 ENSO event. We treated rainfall level as a proxy for food availability, the ecological cue most relevant to the organism during development.

Figure 2 near here

The primary outcome variable was birth weight (B), and our model assumed that this trait is subject to two opposing tensions. On the one hand, below a certain threshold, birth weight is inadequate for sustaining an infant. This favors increasing birth weight. On the other hand, above a certain upper threshold, fetal growth exceeds the mother's capacity to extract energy from current or recent environments. In other words, we

considered that the challenge for the offspring is to calibrate its fetal growth to ecological conditions in a way that avoids these extreme phenotypes.

Birth weight correlates strongly with adult size, (Li et al., 2003; Sayer at el., 2004; Euser et al., 2005). While larger birth weight brings higher fitness returns in adult life (Wells 2007b), the trajectory of growth towards large adult size is inherently constrained by the availability of maternal resources during early life. This assumption is supported by evidence that human gestation length is constrained by energetic rather than biomechanical factors (Leutenegger 1982; Ellison 2008; Dunsworth et al., 2012).

We posed two key questions: how sensitive should birth weight be to environmental cues; and how can useful information be extracted by the offspring from the crude ecological record?

X.4 The basic model

The model was constructed using a succession of algorithms to simulate how human offspring might process crude ecological information to derive an adaptive growth strategy (**Box 2**). In order to express our results in a way that facilitates comparison with empirical birth weight data, we assigned an average value for B of 3 kg (in other words, we treat this value as a population average that is present now because it approximates to birth weights that maximized fitness in the recent past). The average value for R over the entire period was 79.7 mm, hence we converted all R-data entered into the model into output B-data by dividing by (79.7/3), or 26.6.

Variability in B can be crudely assessed using the coefficient of variation (CV). Although a large CV provides one indication of the risk of excessive or insufficient birth weight values, it is also helpful to see how this risk is distributed. We therefore calculated 'fitness penalties', as the difference between the actual B value and 3 kg. The larger the difference, the more birth weight was inadequate or excessive. These fitness values could be expressed in absolute values or squared to make positive and negative penalties equivalent.

Using this model, we considered a range of information-processing algorithms whereby growth could be calibrated to environmental conditions so as to reduce fitness penalties.

X.5 Simple smoothing

The crudest strategy for adjusting reproductive output to ecological conditions would be for the organism to track R on a month-by-month basis, allowing B to respond to the last available signal of R prior to birth, such that B is proportional to R:

$$B \propto R \qquad \text{(Eq.1)}$$

In the simulation, the standard deviation of R was 109.3 mm. As R fluctuated substantially across every annual cycle (represented by the coefficient of variation (CV) of 137.2%), and B varied proportionately, direct tracking of R produced minimum and maximum values for B of 0 and 18.9 kg respectively, generating a very high proportion of non-viable B values, and hence high fitness penalties.

A simple way to model dampened sensitivity to crude variability in ecological conditions would be to average the response to R over a longer time period (Wells 2003; Kuzawa 2005). For example, the duration of pregnancy allows ecological information to act on the phenotype directly over a 9-month period, which can be represented using a rolling average, as shown here:

$$B \propto 1/9\left(\sum_{t-9}^{t} R\right) \quad \text{(Eq.2)}$$

This rolling average still varied between successive 9-month periods, and it itself had a CV of 40.3%. In order to test whether the variability of B could be further reduced by extending the duration of the period of information processing (i.e., effectively increasing the duration of pregnancy), rolling averages were also calculated over 18-, 27-, 36- and 45-month periods. In each case, the CV for birth weight was calculated, along with squared fitness penalties.

Figure 3 illustrates the decline in CV and the increase in minimum birth weight in relation to lengthening the duration of pregnancy. Integrating information over 36 months or more reduced the CV of birth weight to ~10%, and the range to 2 to 3.7 kg. The fitness penalty declined substantially up to 27 months, but little thereafter. Thus, one way to minimize the likelihood of unviable birth weight would be to 'drip-feed' ecological information into the offspring phenotype over a lengthy time period. However, lengthening pregnancy clearly has other penalties in terms of maternal fitness, as it reduces fertility rate over the entire reproductive career.

Figure 3 near here

Paradoxically, a similar stability in birth weight could be obtained simply by dampening sensitivity to ecological conditions – in other words, by minimizing the weight given to current ecological information. This is equivalent to increasing a genetic constraint on birth weight, and reducing the magnitude of plasticity. For example, a simple strategy in which birth weight was a function of a relatively fixed expectation (3 kg), and allowed to vary only modestly around this value (say, 33% of the actual difference between the 9-month average and 3 kg), also produced very low fitness penalties. When this strategy was used, the CV of birth weight obtained was 12%, the minimum birth weight was 2.19 kg, and the average fitness penalty was 0.13. If fitness penalties can be minimized without significant information-processing, then there must be another axis of ecological variability, not addressed in the modeling so far, that is important. We suggest that one such axis may be long-term ecological trends.

X.6 Long-term ecological trends

The limitations of the fixed 'minimal processing' strategy become evident if we manipulate the raw rainfall data to introduce a downward secular trend over time, thus simulating variability that was not actually evident in our 130 year rainfall data.

The distribution of raw error in rainfall over time was plotted for the two scenarios: (a) no trend over time, versus (b) a downward trend. The resulting CV of birth weight was 12.1% for no trend, and 13.8% for the downward trend. The fitness penalty was 0.13 (SD 0.14) for no trend, but 0.17 (SD 0.19) for the downward trend, indicating relatively similar overall fitness in both scenarios. However, as illustrated in **Figure 4,** the

distribution of the raw (unsquared) fitness penalties for each scenario showed that, whereas penalties were randomly distributed in the absence of any trend in rainfall, they changed systematically across time with the downward trend.

The 'minimal processing' strategy systematically produced birth weight values lower than the optimum during the early part of this downward trend, and higher values than the optimum during the end of the trend. This means that, should a trend ultimately lead to the environment stabilizing at a lower level of rainfall, a 'minimal processing' strategy would remain locked into higher fitness penalties, with birth weights consistently exceeding adaptive levels for the available energy supply. Thus, a fixed strategy cannot accommodate long-term trends, and would be outcompeted by the plastic smoothing strategy described above, allowing sensitivity to ecological signals.

Figure 4 near here

X.7 Generational effects

On the basis that information processing is indeed valued, but cannot be achieved through extending the duration of pregnancy, we considered an alternative algorithm, that could process greater quantities of ecological data.

Since plasticity in each generation is greatest in early life, a maternal effect was introduced to simulate conditions during the mother's own early life. Assuming a generation time of 20 years, the maternal effect was operationalized by integrating rolling averages of the effect of R on B from both the current 9-month period (G0), and a

second 9-month period 20 years earlier (G1). In this model, therefore, both maternal developmental conditions and current maternal conditions could shape the offspring B value. This represents a 1-generation maternal effect, i.e.:

$$\mathrm{B} \;\propto\; 1/18 \left\{ \left(\sum_{t-9}^{t} R \right) + \left(\sum_{t-249}^{t-240} R \right) \right\}$$

(Eq.3)

The model was further developed by adding simulations (G1 through G4) that included up to 5 generations of additional maternal effects. The final model, therefore, simulates the integration by the offspring of information on the current 9-month period (G0), as well as 9-month periods 20 years ago (maternal effects, G1), 40 years ago (grand maternal effects, G2), 60 years ago (great-grandmaternal effects, G3), 80 years ago (great-great grandmaternal effects, G4) and 100 years ago (great-great-great-grandmaternal effects, G5):

$$\mathrm{B} \;\propto 1/54 \left\{ \left(\sum_{t-9}^{t} R \right) + \left(\sum_{t-249}^{t-240} R \right) + \left(\sum_{t-489}^{t-480} R \right) + \left(\sum_{t-729}^{t-720} R \right) + \left(\sum_{t-969}^{t-960} R \right) + \left(\sum_{t-1209}^{t-1200} R \right) \right\}$$

(Eq.4)

Each of these models was run using R-data from the period of 1970 - 2002, and the range and CV of B were calculated. As shown in **Figure 5**, there was a decline in the CV of B with each additional generation of lag for the first 3 generations; adding in further generational effects produced a negligible difference in the outcome.

Figure 5 near here

Since these findings indicated no substantial benefits of integrating data across more than 3 generations preceding the focal developmental period, all subsequent models used just 1 or 3 generations of lag – that is, incorporating either maternal effects or great- grandmaternal effects.

X.8 Buffering extreme events

We next tested the effect of a sudden drastic decline in R in the past, as in an ENSO event. The average annual value for R in the entire data set was 79.7 mm; however three years during this period reflected particularly severe ENSO events, during which the annual average rainfall was markedly lower: 1899 (38.0 mm), 1920 (43.8 mm) and 1970 (50.9 mm).

The model assumed that offspring were born in 1990, twenty years after the 1970 ENSO event, which had therefore occurred during the mothers' own fetal life. Birth weight patterns for offspring were calculated incorporating either 1 or 3 generations of maternal buffering of intergenerational environmental variation, as explained above. When maternal effects only were incorporated, birth weight of offspring dropped as low as ~1.5 kg, whereas when great-grand-maternal effects were applied, the lowest birth weight was ~2.5 kg (**Figure 6**).

Figure 6 near here

This simulation therefore showed that multi-generational damping of environmental effects has the potential to be very successful at buffering offspring from extreme short-term perturbations experienced by their mother during her own development Only a modest adverse effect is propagated to future generations. In the event that several additional generations are spared such extreme events during fetal life, this adverse effect would be expected to wash out entirely.

X.9 Predicting the future

The final model tested the capacity of offspring birth weight to predict subsequent ecological conditions, as simulated using two different strategies. In the first outcome, a birth weight based on a 9-month rolling average was associated with rainfall in the following month ($r = 0.14$, $p<0.0001$), but not with maternal phenotype at 1 year ($r = 0.02$, ns), or with rainfall 20 years in the future, either averaged over 1 year ($r = 0.03$, ns) or 20 years ($r = 0.05$, ns). In this approach, maternal phenotype at 1 year was calculated as a rolling average over the previous 12 months.

Using the 3-generation lagged model for birth weight, there was no correlation between offspring phenotype at birth and rainfall in the subsequent month ($r = -0.09$, ns) (**Figure 7a**), as birth weight values are now dominated by maternal effects rather than current conditions. On the other hand, a strong correlation was found between offspring phenotype at birth and maternal phenotype 1 year later ($r = 0.62$, $p<0.0001$)(**Figure 7b**). Since both offspring and maternal phenotype reflect the maternal signal smoothed over 3 generations, this demonstrates how maternal phenotype can represent a stable

ecological signal in the immediate postnatal period, regardless of how the external environment actually changes during this time. **Figures 7c** and **7d** show, further, that there was no correlation between offspring phenotype at the time of birth and a 1-year average of R 20 years in the future (i.e., ecological conditions when the offspring will reach reproductive maturity)(r = -0.08, ns), or a ten-year average of R commencing 20 years in the future (i.e., ecological conditions during the offspring's reproductive career)(r = -0.08, ns). Thus, the results of this simulation suggest that information extracted from maternal phenotype in early life cannot match the offspring's phenotype with ecological conditions encountered in adult life.

Figure 7 near here

X.10 Discussion

We used a simple mathematical simulation model based on an actual historical data set of ecological conditions to investigate different strategies whereby offspring might adaptively process information relevant to fitness during early, sensitive periods of development. The challenge facing the offspring was to be able to respond to ecological stresses in early life, but not to the extent that growth patterns became extreme. We then considered whether strategies that solved this dilemma could match the organism's phenotype with ecological conditions in adulthood. The main findings were as follows.

First, even crude processing of available information is a more adaptive strategy than ignoring ecological cues altogether, and has the potential to reduce the likelihood of

unviable birth weight whilst also tracking long-term ecological trends. Although a new genetic set-point for birth weight could evolve over many generations, such an evolutionary process would be very slow relative to the actual rate of ecological change. Consistent with this argument, relatively little of the variance in human birth weight can be accounted for by genetic factors (Magnus et al., 2001; Lunde et al., 2007).

Second, while lengthening the period over which ecological information is collected should help buffer short-term variability, there is a limit to how far this strategy can be applied, given that it imposes costs on maternal fertility. Thus, lengthier pregnancies eventually become an inefficient way of smoothing ecological signals and constraining extreme growth patterns. This result is supported by recent work demonstrating that the maternal energy budget is insufficient to support lengthier human pregnancies (Ellison 2008; Dunsworth et al., 2012; Wells et al., 2012).

Third, an alternative, beneficial damping effect can be introduced by incorporating maternal effects, and this effect can be multiplied across several successive generations. In our simulation, little additional benefit accrued beyond 3 generations of lag; however, the outcomes of this scenario might vary according to the degree of ecological stochasticity. Biological mechanisms for such lags may involve epigenetic marks, though the available evidence suggests that these are only rarely transmitted directly across generations (Youngson and Whitelaw 2008; Hackett et al., 2013). In the female line, the ovum that contributes to each offspring has already been exposed to the maternal uterine environment - and hence the grandmaternal phenotype - allowing grandmaternal effects to be transmitted directly to grandoffspring (Youngson and Whitelaw 2008; Drake and Liu 2010).

Fourth, such a multi-generational damping strategy could be very effective at avoiding the propagation of effects of severe ecological shocks to future generations. A mother born during an ENSO event is relatively well buffered by the 3-generation lag, so that her own offspring is only moderately below the optimal birth weight. We consider this protective effect especially valuable, since size in early life is highly predictive of infant survival (Hogue et al., 1987), and infancy is the period of greatest extrinsic mortality risk in our species (Kelly 1995).

Fifth, although the ecological information extracted via the maternal phenotype allowed accurate short-term predictions using that maternal source of information, none of the strategies for information processing used in our simulations demonstrated any ability to predict long-term future conditions. Neither a short-term index, as proposed by Gluckman and Hanson (2004a, b; 2007), nor an index smoothed across several ancestral generations, as proposed by Kuzawa (2005), showed any correlation with long-term future conditions. There was, however, a short-term correlation between offspring birth phenotype and maternal phenotype 1 year after birth,.

These simulations therefore provide support for the maternal capital model of developmental plasticity (Wells 2003; 2010; 2012c), but not for models that assume that developmental plasticity enables fetal/infant phenotype to vary in anticipation of future ecological conditions (Kuzawa 2005; Gluckman and Hanson 2004a; b). The results of these simulations are also consistent with epidemiological studies which have shown that fetal growth is relatively resistant to short-term spikes or troughs in maternal energy intake, as reviewed previously (Wells 2003; Kuzawa 2005). The results

regarding the inability to predict future conditions, moreover, are consistent with previous simulations (Wells, 2007a; Baig et al., 2011).

The fact that short-term predictions are possible in our model shows that the offspring can make a prediction about the nutritional supply likely to be available immediately after birth, during the lactation period. Since both the signals being processed, and the nutritional supply after birth, derive from maternal phenotype, this effectively means that the fetus can calibrate its growth to the likely supply of breast-milk during infancy.

This is a specific prediction of the maternal capital hypothesis which, unlike other models, assumes that the primary fitness benefit of developmental plasticity is to enable a close match between offspring growth trajectory and maternal phenotype (Wells, 2003; 2012c). However, another key reason why selection favours a match between maternal phenotype and offspring growth is that every fetus must avoid growing beyond the dimensions of the maternal pelvis (Wells et al., 2012; Wells 2015).

The use of a simulation model to explore human adaptation has some strengths, as it allows comparison of different strategies across several generations, an approach rarely possible using data on humans themselves. However, the model also neglected some potentially important issues. For example, information does not only enter phenotype during the 9-month period of pregnancy each generation. A more realistic model would allow information to enter phenotype over longer time periods, hence our model only investigates the effect of multi-generational lags acting on pregnancy. Similarly, human developmental plasticity extends into infancy, and growth during infancy can resolve some of the variability that characterizes birth weight, however this was not addressed.

Despite these limitations, the model is valuable in demonstrating how maternal effects can damp ecological perturbations including extreme events. The same buffering process may have been important in enabling humans to migrate between contrasting ecological niches, by damping offspring from sudden shifts in nutritional supply during the most sensitive period of development (Wells, 2012c). Thus, the fact that developmental plasticity does not allow forecasting of long-term adult environments does not mean that the process has no adaptive value. Rather, developmental plasticity in early life appears of greatest value in promoting survival during early life, a time when extrinsic mortality risk is high. This issue has important implications for public health policies aimed at addressing chronic malnutrition, as it suggests that continued maternal buffering via lactation may help prevent catch-up 'overshoot' in the early postnatal period. Rapid catch-up growth has been shown to accelerate markers of cellular aging, and is associated with adult chronic disease risk (Metcalfe and Monaghan 2001).

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Legends for illustrations

Figure 1. A schematic diagram of variation in ecological conditions over time, illustrating three components of variability: (a) regular cycles, such as seasonality; (b) long-term systematic trends such as climate change; and (c) extreme perturbations, such as El Niño Southern Oscillation (ENSO) events. Note that we simulated the second component (long-term ecological trend) as it was not actually evident in our 130 year rainfall data.

Figure 2. The pattern of rainfall in the Indian data set used for this model, showing raw monthly values and average annual values.

Figure 3. The effect of increasing the period of information processing (equivalent to increasing the duration of pregnancy) on variability in birth weight. (a) Lengthening pregnancy decreases the coefficient of variation and increases the minimum value. (b) Lengthening pregnancy decreases the fitness penalties arising from suboptimal birth weights.

Figure 4. The distribution of fitness penalties when information processing is minimal in different types of environment. (a) In a stable environment, fitness penalties are randomly distributed. (b) In an environment systematically declining in productivity over time, fitness penalties are not randomly distributed, and may become systematically high since the phenotype cannot adjust to the ecological change.

Figure 5. The effect of introducing maternal effects (which buffer short-term ecological variability) across increasing numbers of generations on variability in birth weight. (a) For the first three generations, each extra generation of lag increases buffering, decreases the coefficient of variation, and increases the minimum value of birth weight. (b) For the first three generations, increased buffering also decreases the fitness penalties arising from suboptimal birth weights. However, for all outcomes, benefits are minimal when extending maternal effects across 4 or 5 generations.

Figure 6. The effect of 1 versus 3 generations of maternal effects, or buffering ecological variability, on offspring birth weight following an extreme event at the time of the mother's birth. The impact of this maternal stress on the offspring's birth weight is greatly reduced by the multi-generational buffering process.

Figure 7. Associations between offspring birth weight (derived from 3 generations of maternal buffering) and four different sets of subsequent ecological conditions. The results show: (a) no significant correlation between birth weight and rainfall in the month immediately following birth; (b) a strong correlation between birth weight and maternal phenotype 1 year later (both derived using the same 3-generation lag approach, but with a time lag of 1 year between the two parties, and expressed in the same smoothed units as birth weight) ($r = 0.62$, $p<0.0001$); (c) no correlation between birth weight and a 12-month average commencing 20 years in the future (representing the time of attaining reproductive maturity); (d) no correlation between birth weight and a 10-year average commencing 20 years in the future (representing the duration of the reproductive career).

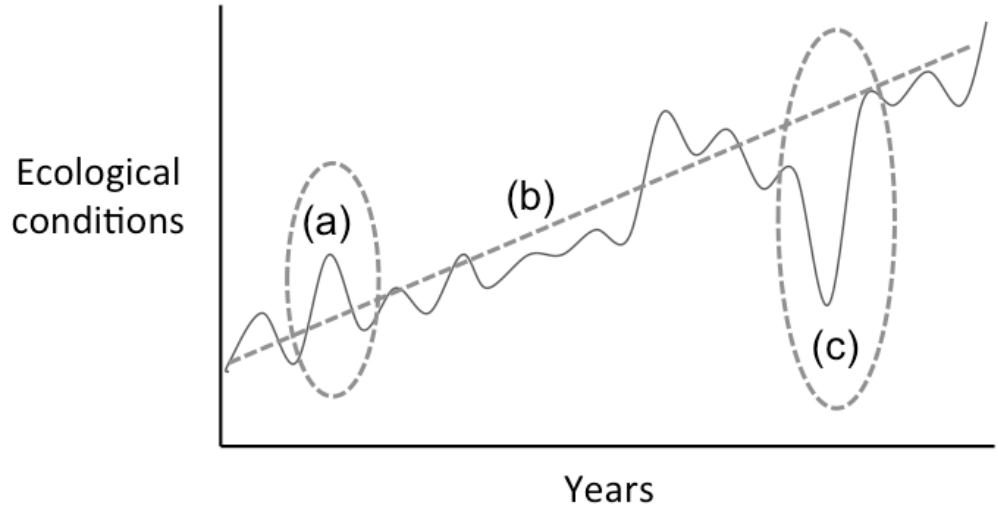

Figure 1

Figure 2

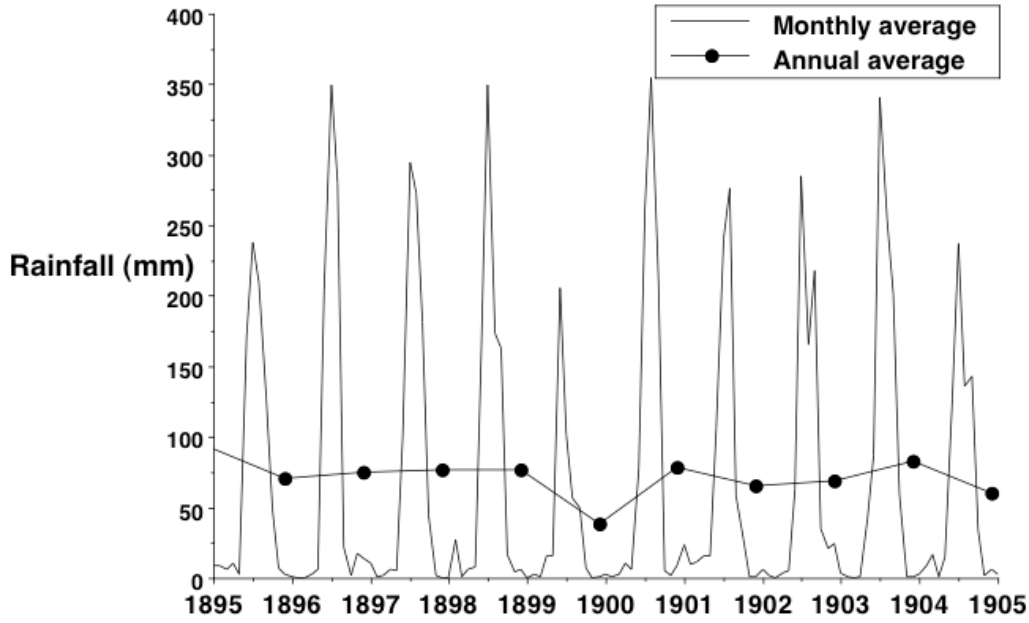

Figure 2

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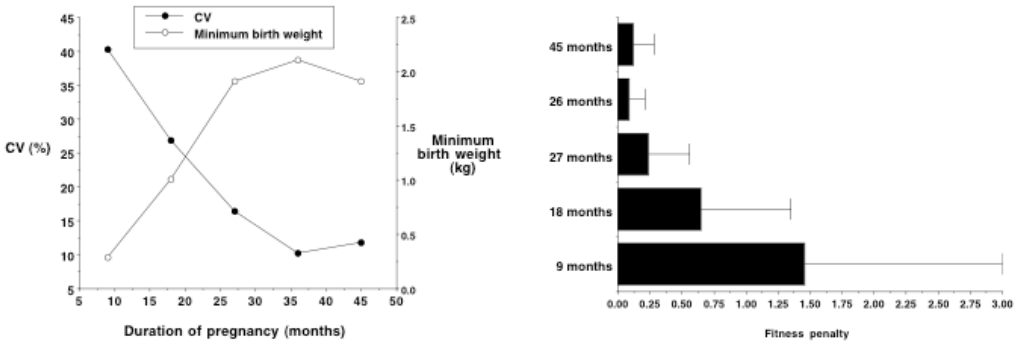

Figure 3

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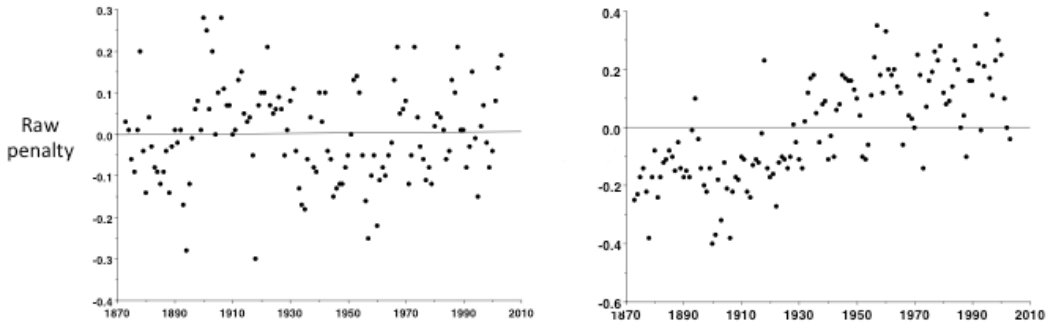

Figure 4

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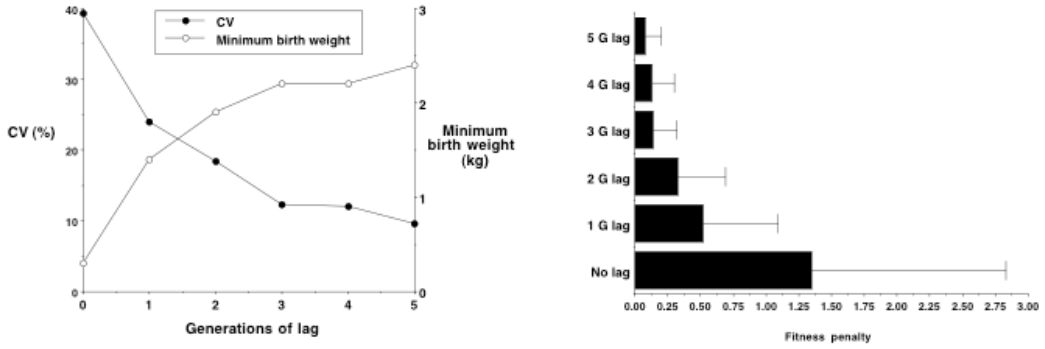

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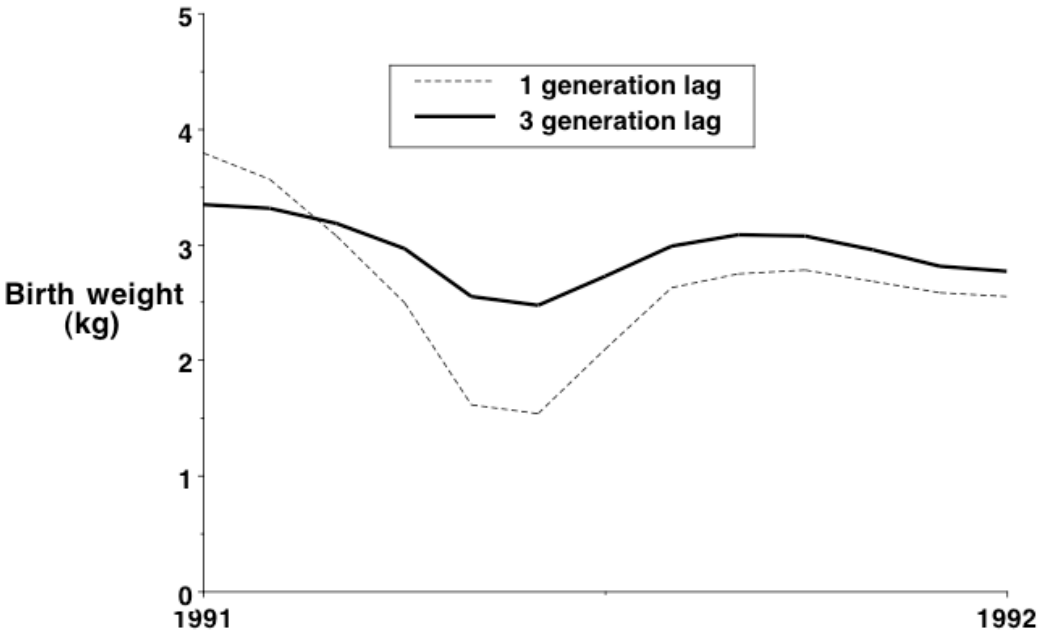
Figure 6



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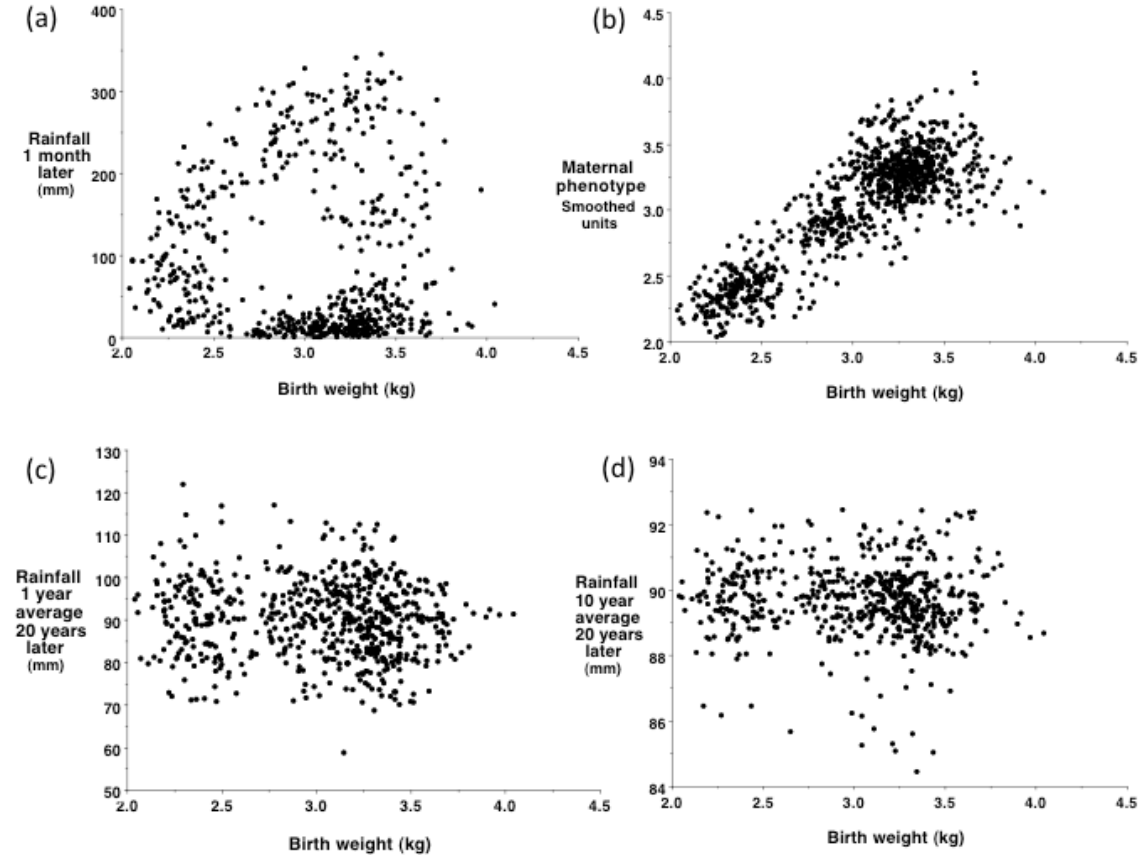

Figure 7