

Article

## Developmental plasticity in deep time: a window to population ecological inference

Anieke Brombacher\* , Daniela N. Schmidt, and Thomas H. G. Ezard

**Abstract.**—Developmental plasticity, where traits change state in response to environmental cues, is well studied in modern populations. It is also suspected to play a role in macroevolutionary dynamics, but due to a lack of long-term records, the frequency of plasticity-led evolution in deep time remains unknown. Populations are dynamic entities, yet their representation in the fossil record is a static snapshot of often isolated individuals. Here, we apply for the first time contemporary integral projection models (IPMs) to fossil data to link individual development with expected population variation. IPMs describe the effects of individual growth in discrete steps on long-term population dynamics. We parameterize the models using modern and fossil data of the planktonic foraminifer *Trilobatus sacculifer*. Foraminifera grow by adding chambers in discrete stages and die at reproduction, making them excellent case studies for IPMs. Our results predict that somatic growth rates have almost twice as much influence on population dynamics than survival and more than eight times more influence than reproduction, suggesting that selection would primarily target somatic growth as the major determinant of fitness. As numerous paleobiological systems record growth rate increments in single genetic individuals and imaging technologies are increasingly available, our results open up the possibility of evidence-based inference of developmental plasticity spanning macroevolutionary dynamics. Given the centrality of ecology in paleobiological thinking, our model is one approach to help bridge eco-evolutionary scales while directing attention toward the most relevant life-history traits to measure.

Anieke Brombacher and Thomas H. G. Ezard. School of Ocean & Earth Science, University of Southampton, Waterfront Campus, National Oceanography Centre, Southampton SO14 3ZH, U.K.  
E-mail: [Anieke.Brombacher@soton.ac.uk](mailto:Anieke.Brombacher@soton.ac.uk), [T.Ezard@soton.ac.uk](mailto:T.Ezard@soton.ac.uk)

Daniela N. Schmidt. School of Earth Sciences and Cabot Institute, University of Bristol, Bristol BS8 1RJ, U.K.  
E-mail: [D.Schmidt@bristol.ac.uk](mailto:D.Schmidt@bristol.ac.uk)

Accepted: 11 July 2022

\*Corresponding author.

### Introduction

The existence of plastic traits, whereby one genotype can produce multiple phenotypes depending on external cues (e.g., temperature-dependent sex ratios in reptiles [Sarre et al. 2004], nutrition-determined caste assignment in female honeybees [Slater et al. 2020]), is ubiquitous. Development of a phenotype best suited to the prevailing environment increases an individual's chances of survival and enables individuals within a population to adapt rapidly to changing environmental conditions within a generation, rather than having to wait for the spread of favorable mutations (West-Eberhard 2003). Especially when faced with regular

change and/or extreme events, plastic traits in individuals can increase chances of population survival (Baldwin 1896; Simpson 1953; Richter-Boix et al. 2006; Chevin and Lande 2009). Plastic traits potentially also enhance species survival over longer timescales. However, the effects of developmental plasticity on macroevolutionary processes and the emergence of new species have long been ignored (West-Eberhard 2003, 2008; Pfennig et al. 2010; Pfennig 2021), largely due to a lack of fossil records with the necessary fine-scale environmental resolution to identify what plasticity uses as a cue.

West-Eberhard (2003) argued that plastic traits can influence both phenotype and genotype frequency in a population through a

process called genetic assimilation. A new environmental cue will cause a plastic trait to be expressed in a novel way, and if this new phenotype has a positive effect on fitness, it will likely be selected for, increasing the frequency of both the phenotypic and genetic components (West-Eberhard 2003, 2005). Plasticity is typically studied through single genotypes, either by examining among-individual variation within families or clones or by taking repeated measurements on the same individual exposed to different environments. The second of these routes is amenable to study in the fossil record (Lister 2021) and our focus here. Modeling studies suggest that moderate plasticity, with plastic traits that are reasonably well, but not perfectly, adjusted are most likely to drive evolutionary innovation: suboptimal adaptation provides the opportunity to move to a new space on the adaptive landscape and can encourage the evolution of better-adapted traits (DeWitt et al. 1998; Price et al. 2003; Ghalambor et al. 2015; Murren et al. 2015). Many studies have since recognized the potential evolutionary implications of developmental plasticity (e.g., Pigliucci et al. 2006; Pfennig et al. 2010; Beldade et al. 2011; Moczek et al. 2011) and increasingly recognize it as a central aspect of evolution, rather than an occasional “add-on” (Laland et al. 2015; Moczek 2015). As a result, several authors have proposed expanding the modern synthesis, which merged Darwinian natural selection and Mendelian inheritance and therefore focuses mainly on mutation-driven change, into an extended evolutionary synthesis (e.g., Pigliucci 2007; Pigliucci and Müller 2010; Laland et al. 2015). However, the need for an extended synthesis is still a topic of lively debate (e.g., Dickins and Rahman 2012; Futuyma 2017; Lu and Bourrat 2018). Opponents argue that no conceptual change is necessary to incorporate developmental processes into the existing synthesis (Futuyma 2017; Lu and Bourrat 2018), as the structure and content of the extended synthesis are still incomplete (Fábregas-Tejeda and Vergara-Silva 2018; Buskell 2019). In the case of evolutionary developmental biology, this is largely due to a lack of empirical data (Levis and Pfennig 2016, 2020; Futuyma 2017). To decide if, and if so, how much, the modern synthesis needs to be adjusted with regard to

developmental plasticity, we must first know the frequency with which long-term plasticity-led evolution occurs in nature (Kovaka 2019).

Most studies investigating the effects of developmental plasticity on evolution focus on extant populations. Laboratory studies on live individuals can determine the full range of responses to external cues as well as provide insights in the effects of plasticity over several generations (e.g., Waddington 1953). Field studies of wild populations provide evidence of genetic accommodation and adaptation by comparing reaction norms in closely related species (Schlichting and Wund 2014), and many such studies have found signs of plasticity-led evolution. Work on spadefoot toads, for example, has shown that a novel diet released cryptic variation that resembled the derived feeding mechanism of its descendant (Ledon-Rettig et al. 2010), suggesting that developmental plasticity helped the descendant species adapt to a new diet.

However, there are several major drawbacks to studying the drivers of evolution using only extant populations. More than 99% of all species that ever lived are now extinct (Stearns and Stearns 1999). Modern species provide no direct information on past evolutionary transitions, and therefore excluding extinct species will make it impossible to assess the frequency of plasticity-led evolution in the past and its relative importance in the winners and losers of historical ecological interactions (Quental and Marshall 2010). Fossils contain information on both macroevolutionary transitions and microevolutionary change, allowing morphological evolution to be quantified through time and across plausible ancestor–descendant pairs rather than an ancestor-proxy of the descendant’s closest living relative (Love et al. 2021). The lack of contemporaneous environmental and morphological data in ancestral forms makes it harder to find direct evidence for plasticity-led evolution (Kovaka 2019). In systems that ally strong phylogenetic understanding with high stratigraphic and environmental resolution, evolutionary change can be studied through speciation intervals and post-speciation divergence (Lazarus 2011; Pearson and Ezard 2014).

Analyzing variation in somatic development of single genetic individuals is a particularly

promising avenue for research into plasticity in the fossil record (Lister 2021). Growth rates can be reconstructed from fossils when ontogeny is preserved in the skeleton, such as from lines of arrested growth in amphibians and reptiles. Several studies have indeed found evidence for plasticity in growth rates in dinosaurs (Sander and Klein 2005) and extinct amphibians (Sanchez et al. 2010; Gee et al. 2020). However, patterns in highly variable traits can only be detected with large sample sizes (Gee et al. 2020), which are rare in the vertebrate fossil record. As the fossil record contains no genetic information, and it is impossible to determine clonal reaction norms of extinct species by laboratory studies, the effects of environmentally dependent variation in somatic growth are still not well understood in deep time (e.g., Moss et al. 2016).

Ideally, we would bring the past and present together by using techniques that span the two communities. The combination of somatic growth, senescent declines, reproductive windows, and trade-offs between survival and fertility adds fundamental biodemographic aspects critical to ecological dynamics. Here, we leverage one such approach with these capabilities—an integral projection model (Easterling et al. 2000)—to investigate the potential for such models to provide insight given the alternative temporal dimensions of paleobiological data. By embedding somatic growth and development centrally within the model assumptions (not all individuals are equally likely to reproduce nor to survive at each developmental stage [Caswell 2001]), we can better match an inferred historical population with an age profile closer to living populations rather than relying on the biased assemblage preserved in the sediment. Our conclusions chart a path to identify the most biodemographically relevant life-history traits to measure when investigating evolutionary ecology in deep time.

### The Model

Integral projection models (IPMs) are drawn from population ecology to describe the dynamics of populations whose demography is regulated by a continuous trait, such as

size, that grows in discrete intervals (Easterling et al. 2000; Ellner et al. 2016). The continuous trait impacts demographic probabilities of survival and reproduction. For example, larger individuals might have a different risk of mortality than smaller ones or might reproduce more successfully than smaller individuals, all else being equal. The outputs from the model track an individual's journey through life. The use of such structured population models therefore has the fundamental advantage over unstructured models, in that individuals do not need to be assumed as equally influential in determining population dynamics.

The fundamental building block of an IPM is the kernel (eq. 1). The kernel is a function that aggregates the chances of survival, growth, and reproduction of individuals into an efficient mathematical expression to project the population dynamics into the future. Different kernels can take on simpler or more complex forms depending on the intended demographic model; Rees et al. (2014) provide step-by-step general instructions for implementing IPMs and further descriptions of adaptations for particular life-history scenarios. Since the introduction of IPMs, increasingly complex demographic scenarios have been envisaged and represented by increasingly complex birth and death models (Ellner and Rees 2006). We adapt one of the more straightforward scenarios from Ellner and Rees (2006) to study the relative importance of births, deaths, and development on the evolution of the focal life history.

The kernel is used to project the population forward in time—the population at a point in time can be described by the sum of the demographic contributions from all individuals alive at the preceding time step:

$$n(z_{t+1}, t + 1) = \int_U^L K(z_{t+1}, z_t) n(z_t, t) dz \quad (1)$$

Here  $n$  is a vector that describes the population given a continuous structuring trait  $z_t$  (here: size) at time  $t$ .  $U$  and  $L$  represent minimum and maximum size, respectively.  $K$  is the kernel representing all possible transitions from size  $z_t$

to size  $z_{t+1}$ , which can be more fully written as  $K(z_t, z_{t+1}) = P(z_t, z_{t+1}) + F(z_t, z_{t+1})$ , where  $P$  represents survival and  $F$  represents fertility. Both  $P$  and  $F$  can be further split into constituent components:  $P$  is size-dependent survival from time  $t$  to  $t+1$  and contemporaneous progression (here: growth) from size  $z_t$  to  $z_{t+1}$ ;  $F$  represents the probability of reproducing as a function of  $z$  and potentially the number of offspring.  $K(z_t, z_{t+1})$  therefore is built from the key building blocks that track an individual's journey through a life cycle characteristic of the species.

Having established an integrable IPM, we then use eigendecomposition to probe the structure of  $K(z_t, z_{t+1})$  and distill key features of the population dynamics and life-history evolution (Ellner et al. 2016). By analyzing the IPM kernel, we can quantify the relative importance of the different demographic processes and their impact on mean population fitness. We do this in two principal ways. First, we use the right and left eigenvectors associated with the dominant eigenvalue to study, respectively, the population structure and reproductive value of each size class. By decomposing  $K$  into these two eigenvectors, we establish a simpler representation of the essential behavior of the system to estimate the proportion of individuals in each size class (the population structure) and the mean fecundity of the individuals that survived to each stage (the reproductive value). Both of these quantities are deeply relevant to project the population dynamics and the selective effects on individuals at different life stages (Taylor 1990) but are challenging to study in the fossil record. Second, we use elasticity analysis. Elasticities quantify the relative influence of each demographic rate on a demographic parameter of interest (Caswell 2007), in this case the projected population growth ( $\lambda_1$ ), and thus mean population fitness, at equilibrium in a deterministic environment. A parameter with a higher elasticity is more influential in determining  $\lambda_1$ . Given the link between population growth and mean population fitness, elasticities are proportional to selection gradients. Elasticities are comparable relative to one another within a particular IPM, such that a rate with twice the elasticity is twice as

important in determining population growth and assumed to be proportional to a selection pressure that is twice as strong. Elasticities of lower-level parameters can also be summed to get the overall influence of mortality, fertility, and somatic growth on the evolution of the life history. Taken together, these outputs of  $K(z_t, z_{t+1})$  thus provide insight into the population ecology and evolutionary pressures experienced by extinct organisms during their lives.

*An IPM for Trilobatus sacculifer.*—Here we implement an IPM to the planktonic foraminifer *Trilobatus sacculifer* Brady, 1877 (Spezzaferri et al. 2015). Planktonic foraminifera have a life history that is ideally suited to representation as an IPM: they grow in discrete stages (chambers; see Fig. 1 and Caromel et al. [2016]) deposited rapidly every two to three days and die after reproduction (Hemleben et al. 1989). After death, shells settle on the seafloor, where their entire ontogeny is preserved in the sediment, resulting in a rich fossil record that reaches back to the Jurassic (Kendall et al. 2020). Plankton net and sediment trap studies allow linking of the developmental history and environmental records (Bijma et al. 1990; Bijma and Hemleben 1994; Mikis et al. 2019).

We take survivorship and probability of reproduction data from laboratory culture experiments by Bijma and Hemleben (1994) and the growth from one stage to the next from Schmidt et al.'s (2013) X-ray computed tomography reconstruction of the developmental history. The chance of survival per size class from Bijma and Hemleben (1994) is converted to chance of survival per ontogenetic step (i.e., addition of a chamber) by taking the  $n^{\text{th}}$  root of survival per size class, with  $n$  being the number of ontogenetic steps per size class (Schmidt et al. 2013). Using the empirical size, survivorship, and probability reproduction data, we determine the remaining parameters of demographic equations (eqs. 2–4) commonly used in population ecology (e.g., Ellner and Guckenheimer 2006; Ellner and Rees 2006). We parameterize the smooth expressions describing the demographic rates of survival, reproduction, and growth as a function of size using non-linear least-squares regression in the R environment for statistical and graphical computing (v. 4.0.2; R Core Team 2020). Our fully annotated

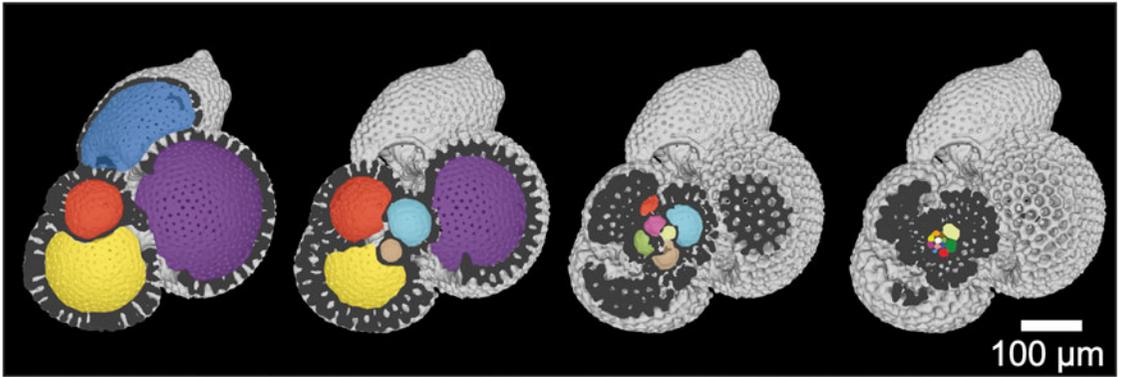


FIGURE 1. *Trilobatus sacculifer* internal structure. Every colored chamber represents a single step in the ontogeny.

TABLE 1. Values fit to parameters stated in the vital rate expressions (eqs. 2–4) with descriptions of their interpretation.

Symbol	Value	Description
$s_1$	0.16	Linear increase in survival probability
$s_2$	$-3.2 \times 10^{-7}$	Scaling of the exponential term $s_3$
$s_3$	2.18	Nonlinear rate of increase in mortality with age (senescence)
$f_1$	0.77	Asymptotic probability of reproduction
$f_2$	9.63	Rate of increase in the probability of reproduction
$f_3$	5.71	Sigmoidal midpoint during the transition from zero to asymptotic probability of reproduction
$g_1$	1.0768	Growth rate from one chamber to the next
$g_2$	0.0238	Standard deviation in one-step growth rate
$g_3$	0.185	Variance exponential in growth
$\zeta$	0.013	Recruitment rate to the population: set to ensure $\lambda_1 = 1.01$ (except in Fig. 5), where $\lambda_1$ represents population growth rate in a deterministic environment
$\mu_{off}$	2.6	Mean size of offspring (ln scale, equivalent to 13.5 $\mu\text{m}$ )
$\sigma_{off}$	0.1	Standard deviation in size of offspring (ln scale, equivalent to an approximate 95% confidence interval of initial stage size of [11.0, 16.5] $\mu\text{m}$ )

and executable R script, from data entry through nls fitting and IPM implementation (based on an appendix to Ellner and Rees [2006]), is in Supplementary Code 1.

The model for survivorship takes the form:

$$s_1x + s_2e^{s_3x} \tag{2}$$

The model for the probability of reproduction takes a logistic form:

$$\frac{f_1}{1 + e^{f_2(x - f_3)}} \tag{3}$$

The model for somatic growth from one stage (chamber) to the next is described by a mean change (eq. 4a) and the standard deviation around it (eq. 4b):

$$\mu_x = g_1x \tag{4a}$$

$$\sigma_x = g_2e^{2g_3\mu_x} \tag{4b}$$

Here  $x$  represents size, and  $\mu_x$  and  $\sigma_x$  represent the mean and standard deviation of the size change from one stage to the next. All other parameters are obtained through nonlinear least-squares regression. Table 1 provides the numeric values obtained through nls() and verbal explanations for the interpretation of each parameter. Through equations (2–4), we can parameterize all demographic rates necessary for  $K(z_t, z_{t+1})$ , except for the rate of recruitment to the breeding population, which, following previous practice, we set to ensure that the long-term growth rate of the population in a deterministic environment was 1.01 (Rees and Rose 2002). Figure 2 shows the statistical fits to the raw data from Bijma and Hemleben (1994) and Schmidt et al. (2013) based on the parameters listed in Table 1. This approach

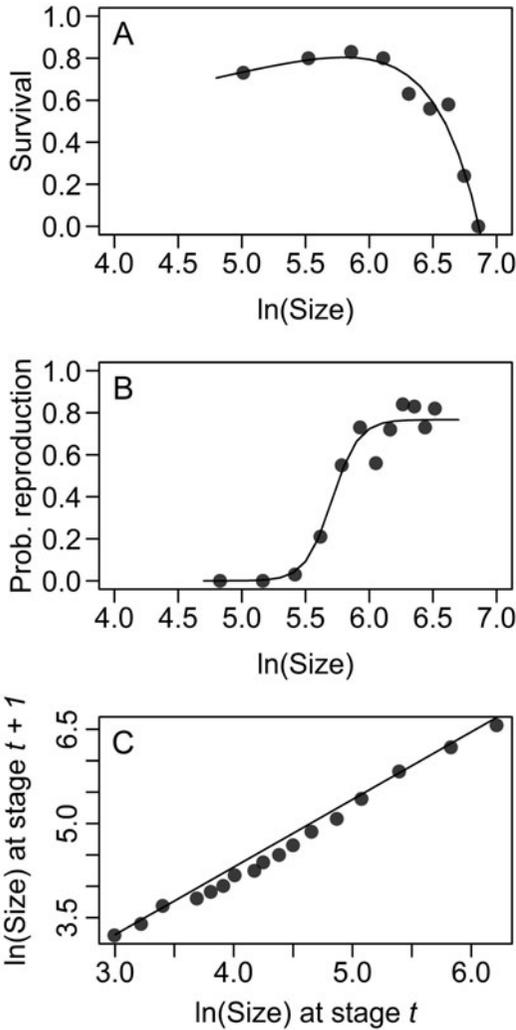


FIGURE 2. Survival (A), probability of reproduction (B), and size at stage  $t + 1$  (C) data and model results from statistical fits to the relationships that feed into the integral projection model kernel. See Table 1 for coefficients.

allows us to study the composition of the projected population as it would have existed, but is not necessarily preserved in deep time, and the relative contribution of each size class to the next generation.

**Results**

The assumed functional forms (eqs. 2–4) provide acceptable fits to the empirical data (Fig. 2), increasing confidence that an IPM based on these inferred relationships captures

the core aspects of the life history of *Trilobatus sacculifer*.  $K(z_t, z_{t+1})$  and its constituent eigenvectors (Fig. 3) make a number of key life-history predictions. Most planktonic foraminifera within a single generation will be the youngest individuals (note the darkest colors in the IPM kernel are in the top right corner,

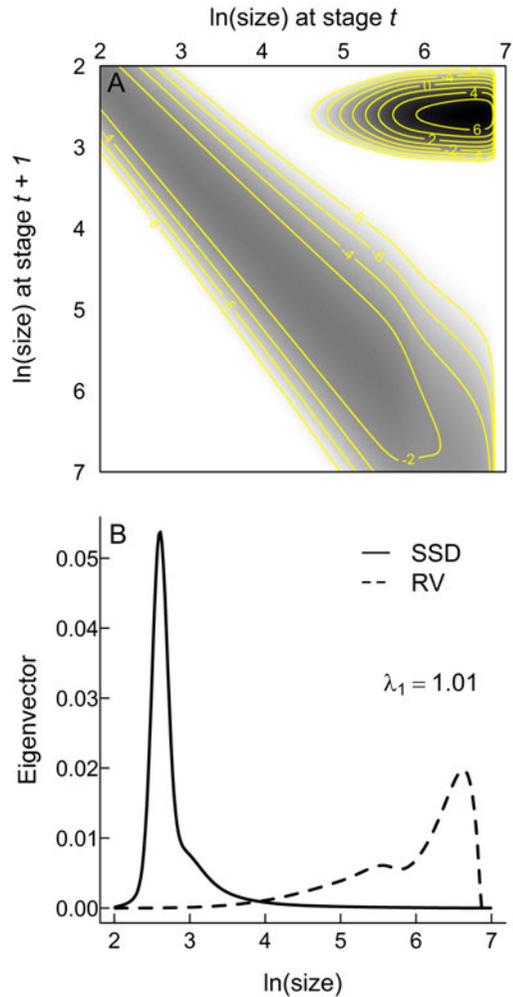


FIGURE 3. Matrix visualization of the integral projection model kernel (A) and the right and left eigenvectors corresponding to the stable stage distribution (SSD) and reproductive value (RV), respectively (B). White areas in A are not accessed by the projected life cycle; grays and blacks indicate the proportions (on an ln scale) of individuals across the life cycle in each stage. The main developmental track is the gray band from top left to bottom right as individuals grow through successive discrete stages. The almost-black peak in the top right corner represents fertility—the transition from the largest stages (at one end of life) to the smallest stages in the next generation. Isolines represent values of the kernel  $K$ .

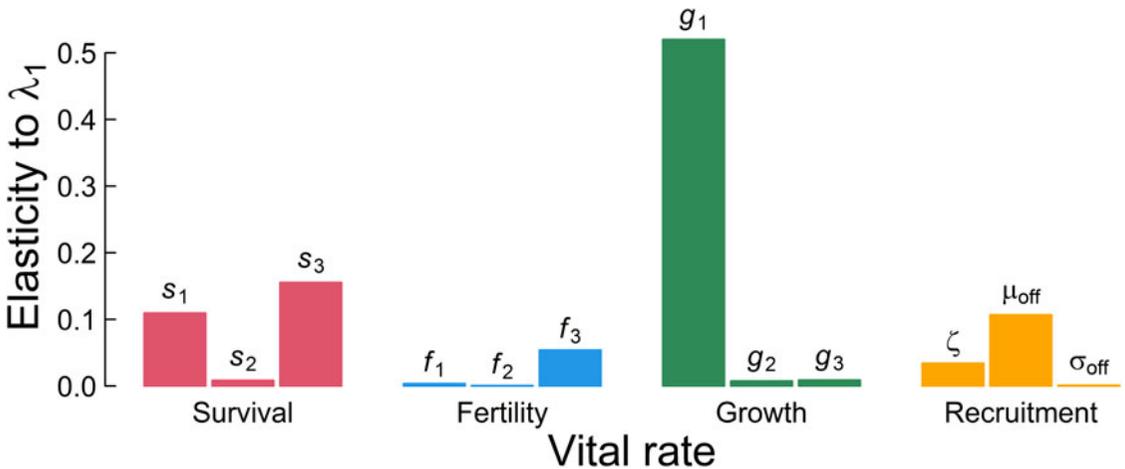


FIGURE 4. Elasticity represents the influence of each parameter on the long-term population growth rate in a deterministic environment  $\lambda_1$ . The three bars within each color indicate lower-level parameters in the order of Table 1 as used to define the aggregated demographic rates.

which represents the transition from adults back to the earliest, one-chambered stage of life [proloculus] through successful reproduction [Fig. 3A] and the peak in the stable stage distribution that gives the relative numbers of individuals per generation at each size [Fig. 3B]). However, the largest rates of mortality are also from those youngest individuals at the beginning of the main developmental track (note the darkest colors in the IPM kernel in the top right, but how the main developmental track from top left to bottom right is a lighter gray; Fig. 3A). The most important individuals for the persistence of the population are the small numbers that reach reproductive maturity (note the reproductive value projection in Fig. 3B), which are those that have the best chance of preservation in the sediment.

Somatic growth rate,  $g_1$ , is the major influence on  $\lambda_1$  (Fig. 4). Summing across the lower-level parameters used in each of the four main demographic rates suggests that somatic growth rate is almost twice as important as survival, eight times more important than whether the individual probably reproduced, and three-and-a-half times more important than recruitment to the breeding population in determining the population ecology. This implies that selection should target somatic growth, because it is the major determinant of mean fitness in these plankton as well as other exponentially

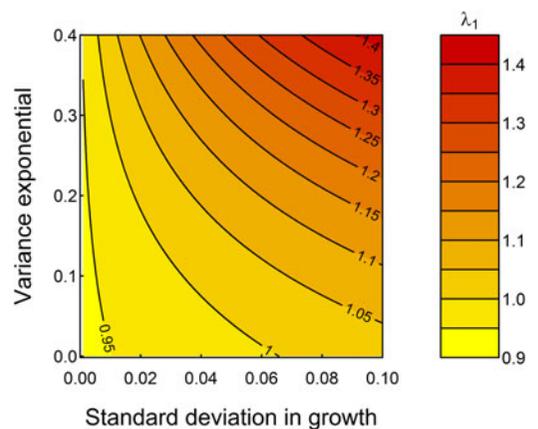


FIGURE 5. Increasing the extent of developmental plasticity by increasing  $g_2$ , the standard deviation in growth, and  $g_3$ , the variance exponential, would be adaptive in the sense of increasing  $\lambda_1$ . The black contours represent different projections for  $\lambda_1$  holding  $\zeta$  as listed in Table 1.

growing and size-regulated organisms well described by this semelparous life history. Therefore, the major signal we need to extract to best understand this population ecology is, reassuringly, something accessible to paleobiological study, as it is preserved in a diversity of organisms and sedimentary settings.

Figure 5 demonstrates the “what if” power of these models—the mean growth rate assumed is well described statistically (Fig. 2) but does not fully enable comprehensive studies of

variation during an individual's growth. By looping across a range of possible parameter values for the standard deviation in somatic growth increments,  $g_2$ , and the expansion of variation among specimens in later life stages,  $g_3$ , as exemplified by the "saclike" final chamber of *T. sacculifer* compared with its ancestor species *Trilobatus trilobus*, we observe that increasing both parameters would increase  $\lambda_1$  (Fig. 5). Specifically, fitness is highest at highest growth rate variation among, as well as within, specimens. The relationship between  $g_2$  and  $g_3$  is not consistent: when  $g_2$  is small, small increases in  $g_2$  rapidly increase  $\lambda_1$ , but the change to population mean fitness is more evenly balanced between  $g_2$  and  $g_3$  when these parameters are larger, and thus developmental plasticity is greater. Figure 5 predicts that, all else being equal, selection should seek to increase developmental plasticity (fitness is highest in the top right corner of Fig. 5). This, and the importance of growth on fitness imply that plasticity in growth is an ecologically meaningful metric of developmental plasticity that can be studied in deep time.

## Discussion

Studies of growth rate variation through time can provide new information on the effects of developmental plasticity on long-term evolutionary change. While the fossil record holds an enviable record of temporal change at the largest scales, sufficiently quantifying fine-scale variation within an individual's journey through life or among individuals within populations is typically far less accessible given taphonomic challenges. Our IPM predicts that a focus on individual (somatic) growth for organisms with a semelparous lifestyle can yield biologically relevant traits expected to be under the strongest selection pressure (Fig. 4). The model helps to determine the paleoecological population context (Fig. 5) that is deeply relevant yet often absent in deep time, even for the most well-studied and charismatic species (e.g., Marshall et al. 2021).

Outputs from models such as the IPM we present can shape new directions in inferring relevant ecological and evolutionary processes

in deep time. Planktonic foraminifera are ideally suited in this regard due to their abundant preservation in seafloor sediments (e.g., Hemleben et al. 1989; Fraass et al. 2015; Fenton et al. 2021), the existence of a species-level phylogeny for all Cenozoic macroperforate planktonic foraminifera (Aze et al. 2011), and the capacity to extract tied morphological and environmental signals from the same specimens (Kearns et al. 2021). Predictions based on this group have broader utility due to the generality of logarithmic spires in nature (McGhee 2007) and the common preservation of ontogenetic information via morphology in organisms as diverse as bivalves (Moss et al. 2016), trilobites (Whittington 1957), fish (Trueman et al. 2016), trees (Falcon-Lang 2015), and dinosaurs (Sander and Klein 2005; Sanchez et al. 2010).

Isolating developmental or phenotypic plasticity in the fossil record is challenging, as it is typically unclear whether an observed morphological pattern arose through plasticity or genetic mutation. Strong evidence for trait plasticity is provided when a single genetic individual or clonal system shows changes in trait expression throughout its life (Lister 2021). Under stable environmental conditions, expression of life-history traits with the highest influence on population growth were traditionally expected to be resistant to environmental change (Hilde et al. 2020; but see McDonald et al. 2017). In our IPM, evolution should promote developmental plasticity, because higher levels of variation in growth increments increase mean population fitness (Fig. 5). More generally, selection can favor phenotypic plasticity when a nonlinear positive relationship between the vital rate and environment leads to increased population growth (Koons et al. 2009). That we do not see unfettered increases in plasticity is due, in part, to morphological constraints limiting evolutionary divergence (Goswami et al. 2014). Devoting more energy to measuring trait (co)variability among further morphological traits promises to be instructive in tracking expected evolutionary changes (Renaud et al. 2006; Hunt 2007; Puttick et al. 2014; Haber 2016), particularly the viability of certain trait combinations (Raup 1967). Mutation-driven change is predicted to alter the

mean trait expression without a simultaneous change in variation among individuals. As soon as the environment changes and different traits are expressed plastically, variation among individuals increases and there is more raw material for rapid diversification (Masel 2005; Suzuki and Nijhout 2006; Moczek 2008; Ledon-Rettig et al. 2010; Küttner et al. 2014; Zheng et al. 2019; Vanadzina and Schmidt 2021).

Given a sufficiently highly resolved temporal fossil sequence, initial stasis followed by increased variation during environmental instability can be strong evidence of evolution driven by developmental plasticity (Jackson 2020). A handful of studies has previously focused on variation in the fossil record as evidence of developmental plasticity, but none provided data of change in this plasticity through time. For example, Anton and Kuzawa (2017) show differences in body size variation in *Homo erectus* populations migrating to subtropical and temperate areas, while Schoch (2014) interpreted high variation among populations from different environmental settings as a fossil reaction norm, but both studies dealt with individual snapshot populations, so variation could not be studied through time. We do not see unfettered increases in developmental plasticity in *Trilobatus sacculifer* under different laboratory conditions, nor departures from logarithmic spires (Bé 1980; Bé et al. 1981). This implies a strong morphological constraint on plasticity in this species that regulates growth and thus maintains one-step deviations in growth rates in the yellow areas of Figure 5. When these constraints are relaxed, plasticity is expected to increase. Changing variation through time is stronger evidence for plasticity-led evolution than variation within a single population (Jackson 2020) and could be coupled with data on single genetic individuals or clonal systems (Lister 2021) as well as environmental context. Focusing on groups with enviable stratigraphic records (Lazarus 1994, 2011) is one promising route to studying greater population context on temporally replicated samples.

Levis and Pfennig (2016) propose that a release of cryptic genetic variation following environmental change is an indicator of plasticity-led evolution in extant populations.

The challenge is in contextualizing developmentally sensitive variation into variance within individuals, among individuals, and among populations. Levis and Pfennig (2016) described four criteria to provide evidence of plasticity-led evolution in extant populations: (1) an environmentally induced target trait, (2) release of cryptic variation in a derived environment, (3) change in regulation and/or form in the target trait following environmental change, and (4) adaptive refinement of the target trait in the derived lineage. Jackson (2020) described how criterion 2 could be observed in a very-high-resolution fossil record, but extracting criterion 4 will, even in the presence of a proxy for every individual's microenvironment, rely on model-based inference via statistical tracking of intraspecific variability alongside an independent metric of environmental change. The most promising systems to examine would be a population adapting to a new environmental optimum (Hunt et al. 2008) as an indication of an altered adaptive landscape (Simpson 1953; Arnold et al. 2001).

Genes can, given sufficient time, combine in many ways to form the same trait (Pfennig et al. 2010; Moczek et al. 2011). Following a release of cryptic variation, further evidence that plasticity successfully led to innovation and speciation can be found through ancestor–descendant comparisons that implement the approaches outlined earlier. A change in form of the target trait in the derived lineage compared with the ancestor would suggest genetic accommodation (Levis and Pfennig 2016). Traits showing subsequent adaptive refinement in the descendant lineage are a particularly strong indicator of successful plasticity-led evolution (Levis and Pfennig 2016). Direct inference of ecologically informative trait evolution in a phylogenetic context is available in highly resolved systems where environmental data can also be resolved on a sub-individual basis (Sadekov et al. 2009). Under divergent selection, it is more important to understand the contemporaneous environmental context than always to seek to isolate a particular genetic mechanism (Schluter 2000; Nosil 2012). This context can be observed in the fossil record of, for example, foraminifera (Aze et al. 2011) and bryozoans (Liow et al.

2019) by comparing ancestor and descendant trait distributions before, during, and after speciation as a response to biotic and abiotic ecological and environmental change. Growth traits are readily quantifiable and testable in trait-based ecosystem models (Grigoratou et al. 2021) that investigate the coevolution of life and the planet and alter the longer-term environmental context.

As growth rate is the largest determinant of fitness in our model (Fig. 4), adaptive evolution in growth rates is expected to increase the descendant's population size and, all else being equal, provide a competitive advantage over the ancestor species or ecological competitors. The use of modeling frameworks such as the IPMs presented here focus attention beyond counts and toward ecological significance (Ezard et al. 2016). Focusing on traits such as growth rate increases our ability to make ecologically relevant inferences and build a more comprehensive picture of the paleoecological context when these species were evolving millions of years ago.

### Acknowledgments

We would like to thank M. Weinkauff and an anonymous reviewer for providing constructive comments on earlier versions of this article. This work was supported by the Natural Environment Research Council awards NE/J018163/1 and NE/P019269/1. D.N.S. would like to acknowledge the Royal Society for a Wolfson Merit award.

### Data Availability Statement

Data available from the Dryad Digital Repository: <https://doi.org/10.5061/dryad.t1gljw53>.

### Literature Cited

- Anton, S. C., and C. W. Kuzawa. 2017. Early *Homo*, plasticity and the extended evolutionary synthesis. *Interface Focus* 7:1–15.
- Arnold, S. J., M. E. Pfrender, and A. G. Jones. 2001. The adaptive landscape as a conceptual bridge between micro- and macroevolution. *Genetica* 112:9–32.
- Aze, T., T. H. Ezard, A. Purvis, H. K. Coxall, D. R. Stewart, B. S. Wade, and P. N. Pearson. 2011. A phylogeny of Cenozoic macroperforate planktonic foraminifera from fossil data. *Biological Reviews of the Cambridge Philosophical Society* 86:900–927.
- Baldwin, J. M. 1896. A new factor in evolution. *American Naturalist* 30:441–451.
- Bé, A. 1980. Gametogenic calcification in a spinose planktonic foraminifer, *Globigerinoides sacculifer* (Brady). *Marine Micropaleontology* 5:283–310.
- Bé, A. W., D. A. Caron, and O. R. Anderson. 1981. Effects of feeding frequency on life processes of the planktonic foraminifer *Globigerinoides sacculifer* in laboratory culture. *Journal of the Marine Biological Association of the United Kingdom* 61:257–277.
- Beldade, P., A. R. A. Mateus, and R. A. Keller. 2011. Evolution and molecular mechanisms of adaptive developmental plasticity. *Molecular Ecology* 20:1347–1363.
- Bijma, J., and C. Hemleben. 1994. Population dynamics of the planktic foraminifer *Globigerinoides sacculifer* (Brady) from the central Red Sea. *Deep-Sea Research, part I (Oceanographic Research Papers)* 41:485–510.
- Bijma, J., J. Erez, and C. Hemleben. 1990. Lunar and semi-lunar reproductive cycles in some spinose planktonic foraminifera. *Journal of Foraminiferal Research* 20:117–127.
- Brady, H. 1877. Supplementary note on the Foraminifera of the chalk (?) of the New Britain Group. *Geological Magazine* 4:534–536.
- Buskell, A. 2019. Reciprocal causation and the extended evolutionary synthesis. *Biological Theory* 14:267–279.
- Caromel, A. G., D. N. Schmidt, I. Fletcher, and E. J. Rayfield. 2016. Morphological change during the ontogeny of the planktic foraminifera. *Journal of Micropaleontology* 35:2–19.
- Caswell, H. 2001. *Matrix population models: construction, analysis and interpretation*. Sinauer Associates, Sunderland, Mass.
- Caswell, H. 2007. Sensitivity analysis of transient population dynamics. *Ecology Letters* 10:1–15.
- Chevion, L. M., and R. Lande. 2009. When do adaptive plasticity and genetic evolution prevent extinction of a density-regulated population? *Evolution* 64:1143–1150.
- DeWitt, T. J., A. Sih, and D. S. Wilson. 1998. Costs and limits of phenotypic plasticity. *Trends in Ecology and Evolution* 13:77–81.
- Dickins, T. E., and Q. Rahman. 2012. The extended evolutionary synthesis and the role of soft inheritance in evolution. *Proceedings of the Royal Society of London B* 279:2913–2921.
- Easterling, M. R., S. P. Ellner, and P. M. Dixon. 2000. Size-specific sensitivity: applying a new structured population model. *Ecology* 81:694–708.
- Ellner, S. P., and J. Guckenheimer. 2006. *Dynamic models in biology*. Princeton University Press, Princeton, N.J.
- Ellner, S. P., and M. Rees. 2006. Integral projection models for species with complex demography. *American Naturalist* 167:410–428.
- Ellner, S. P., D. Z. Childs, and M. Rees. 2016. *Data-driven modelling of structured populations*. Springer, Cham, Switzerland.
- Ezard, T. H. G., T. B. Quental, and M. J. Benton. 2016. The challenges to inferring the regulators of biodiversity in deep time. *Philosophical Transactions of the Royal Society of London B* 371:1–11.
- Fábregas-Tejeda, A., and F. Vergara-Silva. 2018. The emerging structure of the Extended Evolutionary Synthesis: where does Evo-Devo fit in? *Theory in Biosciences* 137:169–184.
- Falcon-Lang, H. J. 2015. A calamitalean forest preserved in growth position in the Pennsylvanian coal measures of South Wales: implications for palaeoecology, ontogeny and taphonomy. *Review of Palaeobotany and Palynology* 214:51–67.
- Fenton, I. S., A. Woodhouse, T. Aze, D. Lazarus, J. Renaudie, A. M. Dunhill, J. R. Young, and E. E. Saupé. 2021. Triton, a new species-level database of Cenozoic planktonic foraminiferal occurrences. *Scientific Data* 8:ar160.
- Fraass, A. J., D. C. Kelly, and S. E. Peters. 2015. Macroevolutionary history of the planktic foraminifera. *Annual Review of Earth and Planetary Sciences* 43:139–166.

- Futuyma, D. J. 2017. Evolutionary biology today and the call for an extended synthesis. *Interface Focus* 7:1–13.
- Gee, B. M., Y. Hariady, and R. R. Reisz. 2020. Histological skeletochronology indicates developmental plasticity in the early Permian stem lissamphibian *Dolesempetron annectens*. *Ecology and Evolution* 10:2153–2169.
- Ghalambor, C. K., K. L. Hoke, E. W. Ruell, E. K. Fischer, D. N. Reznick, and K. A. Hughes. 2015. Non-adaptive plasticity potentiates rapid adaptive evolution of gene expression in nature. *Nature* 525:372–375.
- Goswami, A., J. B. Smaers, C. Soligo, and P. D. Polly. 2014. The macroevolutionary consequences of phenotypic integration: from development to deep time. *Philosophical Transactions of the Royal Society of London B* 369:1–15.
- Grigoratou, M., F. M. Monteiro, A. Ridgwell, and D. N. Schmidt. 2021. Investigating the benefits and costs of spines and diet on planktonic foraminifera distribution with a trait-based ecosystem model. *Marine Micropaleontology* 166:1–9.
- Haber, A. 2016. Phenotypic covariation and morphological diversification in the ruminant skull. *American Naturalist* 187:576–591.
- Hemleben, C., M. Spindler, and O. R. Anderson. 1989. *Modern planktic foraminifera*. Springer, New York.
- Hilde, C. H., M. Gamelon, B. E. Sæther, J. M. Gaillard, N. G. Yoccoz, and C. Pélabon. 2020. The demographic buffering hypothesis: evidence and challenges. *Trends in Ecology and Evolution* 35:523–538.
- Hunt, G. 2007. Evolutionary divergence in directions of high phenotypic variance in the ostracode genus *Poseidonamicus*. *Evolution* 61:1560–76.
- Hunt, G., M. A. Bell, and M. P. Travis. 2008. Evolution toward a new adaptive optimum: phenotypic evolution in a fossil stickleback lineage. *Evolution* 62:700–710.
- Jackson, I. S. C. 2020. Developmental bias in the fossil record. *Evolution and Development* 22:88–102.
- Kearns, L. E., S. M. Bohaty, K. M. Edgar, S. Nogué, and T. H. G. Ezard. 2021. Searching for function: reconstructing adaptive niche changes using geochemical and morphological data in planktonic foraminifera. *Frontiers in Ecology and Evolution* 9:ar679722.
- Kendall, S., F. Gradstein, C. Jones, O. T. Lord, and D. N. Schmidt. 2020. Ontogenetic disparity in early planktic foraminifers. *Journal of Micropalaeontology* 39:27–39.
- Koons, D. N., S. Pavard, A. Baudisch, and C. Jessica E. Metcalf. 2009. Is life-history buffering or lability adaptive in stochastic environments? *Oikos* 118:972–980.
- Kovaka, K. 2019. Underdetermination and evidence in the developmental plasticity debate. *British Journal for the Philosophy of Science* 70:127–152.
- Küttner, E., K. J. Parsons, A. A. Easton, S. Skulason, R. G. Danzmann, and M. M. Ferguson. 2014. Hidden genetic variation evolves with ecological specialization: the genetic basis of phenotypic plasticity in Arctic charr ecomorphs. *Evolution and Development* 16:247–257.
- Laland, K. N., T. Uller, M. W. Feldman, K. Sterelny, G. B. Muller, A. Moczek, E. Jablonka, and J. Odling-Smee. 2015. The extended evolutionary synthesis: its structure, assumptions and predictions. *Proceedings of the Royal Society of London B* 282:1–15.
- Lazarus, D. 1994. Neptune: a marine micropaleontology database. *Mathematical Geology* 26:817–832.
- Lazarus, D. 2011. The deep-sea microfossil record of macroevolutionary change in plankton and its study. In A. J. McGowan, and A. B. Smith, eds. *Comparing the geological and fossil records: implications for biodiversity studies*. Geological Society of London Special Publication 358: 141–166.
- Ledon-Rettig, C. C., D. W. Pfennig, and E. J. Crespi. 2010. Diet and hormonal manipulation reveal cryptic genetic variation: implications for the evolution of novel feeding strategies. *Proceedings of the Royal Society of London B* 277:3569–3578.
- Levis, N. A., and D. W. Pfennig. 2016. Evaluating “plasticity-first” evolution in nature: key criteria and empirical approaches. *Trends in Ecology and Evolution* 31:563–574.
- Levis, N. A., and D. W. Pfennig. 2020. Plasticity-led evolution: a survey of developmental mechanisms and empirical tests. *Evolution and Development* 22:71–87.
- Liow, L. H., T. Reitan, K. L. Voje, P. D. Taylor, and E. Di Martino. 2019. Size, weapons, and armor as predictors of competitive outcomes in fossil and contemporary marine communities. *Ecological Monographs* 89:1–15.
- Lister, A. M. 2021. Phenotypic plasticity in the fossil record. Pp. 267–297 in D. W. Pfennig, ed. *Phenotypic plasticity and evolution*. CRC Press, Boca Raton, Fla.
- Love, A. C., M. Grabowski, D. Houle, L. H. Liow, A. Porto, M. Tsuboi, K. L. Voje, and G. Hunt. 2021. Evolvability in the fossil record. *Paleobiology* 48:186–209.
- Lu, Q., and P. Bourrat. 2018. The evolutionary gene and the Extended Evolutionary Synthesis. *British Journal for the Philosophy of Science* 69:775–800.
- Marshall, C., D. V. Latorre, C. J. Wilson, T. M. Frank, K. M. Magoulick, J. B. Zimmt, and A. W. Poust. 2021. Absolute abundance and preservation rate of *Tyrannosaurus rex*. *Science* 372:284–287.
- Masel, J. 2005. Evolutionary capacitance may be favored by natural selection. *Genetics* 170:1359–1371.
- McDonald, J. L., M. Franco, S. Townley, T. H. G. Ezard, K. Jelbert, and D. J. Hodgson. 2017. Divergent demographic strategies of plants in variable environments. *Nature Ecology and Evolution* 1:1–29.
- McGhee, G. 2007. *The geometry of evolution*. Cambridge University Press, Cambridge.
- Mikis, A., K. R. Hendry, J. Pike, D. N. Schmidt, K. M. Edgar, V. Peck, F. J. C. Peeters, M. J. Leng, M. P. Meredith, C. L. Todd, S. Stammerjohn, and H. Ducklow. 2019. Temporal variability in foraminiferal morphology and geochemistry at the West Antarctic Peninsula: a sediment trap study. *Biogeosciences* 16:3267–3282.
- Moczek, A. P. 2008. On the origins of novelty in development and evolution. *BioEssays* 30:432–447.
- Moczek, A. P. 2015. Developmental plasticity and evolution—*quovadis?* *Heredity* 115:302–305.
- Moczek, A. P., S. Sultan, S. Foster, C. Ledon-Rettig, I. Dworkin, H. F. Nijhout, E. Abouheif, and D. W. Pfennig. 2011. The role of developmental plasticity in evolutionary innovation. *Proceedings of the Royal Society of London B* 278:2705–2713.
- Moss, D. K., L. C. Ivany, E. J. Judd, P. W. Cummings, C. E. Bearden, W. J. Kim, E. G. Artruch, and J. R. Driscoll. 2016. Lifespan, growth rate, and body size across latitude in marine Bivalvia, with implications for Phanerozoic evolution. *Proceedings of the Royal Society of London B* 283:1–7.
- Murren, C. J., J. R. Auld, H. Callahan, C. K. Ghalambor, C. A. Handelsman, M. A. Heskell, J. G. Kingsolver, H. J. Maclean, J. Masel, H. Maughan, D. W. Pfennig, R. A. Relyea, S. Seiter, E. Snell-Rood, U. K. Steiner, and C. D. Schlichting. 2015. Constraints on the evolution of phenotypic plasticity: limits and costs of phenotype and plasticity. *Heredity* 115:293–301.
- Nosil, P. 2012. *Ecological speciation*. Oxford University Press, Oxford.
- Pearson, P. N., and T. H. G. Ezard. 2014. Evolution and speciation in the Eocene planktonic foraminifer *Turborotalia*. *Paleobiology* 40:130–143.
- Pfennig, D. W. 2021. Key questions about phenotypic plasticity. Pp. 25–54 in D. W. Pfennig, ed. *Phenotypic plasticity and evolution*. CRC Press/Taylor & Francis Group, Boca Raton, Fla.
- Pfennig, D. W., M. A. Wund, E. C. Snell-Rood, T. Cruickshank, C. D. Schlichting, and A. P. Moczek. 2010. Phenotypic plasticity’s impacts on diversification and speciation. *Trends in Ecology and Evolution* 25:459–467.

- Pigliucci, M. 2007. Do we need an extended evolutionary synthesis? *Evolution* 61:2743–2749.
- Pigliucci, M., and G. B. Müller. 2010. Elements of an extended evolutionary synthesis. Pp. 3–17 in M. Pigliucci and G. B. Müller, eds. *The extended evolutionary synthesis*. MIT Press, Cambridge, Mass.
- Pigliucci, M., C. J. Murren, and C. D. Schlichting. 2006. Phenotypic plasticity and evolution by genetic assimilation. *Journal of Experimental Biology* 209:2362–2367.
- Price, T. D., A. Qvarnstrom, and D. E. Irwin. 2003. The role of phenotypic plasticity in driving genetic evolution. *Proceedings of the Royal Society of London B* 270:1433–1440.
- Puttick, M. N., G. H. Thomas, and M. J. Benton. 2014. High rates of evolution preceded the origin of birds. *Evolution* 68:1497–1510.
- Quental, T. B., and C. R. Marshall. 2010. Diversity dynamics: molecular phylogenies need the fossil record. *Trends in Ecology and Evolution* 25:434–441.
- Raup, D. M. 1967. Geometric analysis of shell coiling: coiling in Ammonoids. *Journal of Paleontology* 41:43–65.
- R Core Team. 2020. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
- Rees, M., and K. E. Rose. 2002. Evolution of flowering strategies in *Oenothera glazioviana*: an integral projection model approach. *Proceedings of the Royal Society of London B* 269:1509–1515.
- Rees, M., D. Z. Childs, and S. P. Ellner. 2014. Building integral projection models: a user's guide. *Journal of Animal Ecology* 83:528–545.
- Renaud, S., J. C. Auffray, and J. Michaux. 2006. Conserved phenotypic variation patterns, evolution along lines of least resistance, and departure due to selection in fossil rodents. *Evolution* 60:1701–1717.
- Richter-Boix, A., G. A. Llorente, and A. Montori. 2006. A comparative analysis of the adaptive developmental plasticity hypothesis in six Mediterranean anuran species along a pond permanency gradient. *Evolutionary Ecology Research* 8:1139–1154.
- Sadekov, A., S. M. Eggins, P. De Deckker, U. Ninnemann, W. Kuhnt, and F. Bassinot. 2009. Surface and subsurface seawater temperature reconstruction using Mg/Ca microanalysis of planktonic foraminifera *Globigerinoides ruber*, *Globigerinoides sacculifer*, and *Pulleniatina obliquiloculata*. *Paleoceanography* 24:1–17.
- Sanchez, S., A. de Ricqlès, R. Schoch, and J. S. Steyer. 2010. Developmental plasticity of limb bone microstructural organization in *Apateon*: histological evidence of pedomorphic conditions in branchiosaurs. *Evolution and Development* 12:315–328.
- Sander, P. M., and N. Klein. 2005. Developmental plasticity in the life history of a prosauropod dinosaur. *Science* 310:1800–1802.
- Sarre, S. D., A. Georges, and A. Quinn. 2004. The ends of a continuum: genetic and temperature-dependent sex determination in reptiles. *BioEssays* 26:639–645.
- Schlichting, C. D., and M. A. Wund. 2014. Phenotypic plasticity and epigenetic marking: an assessment of evidence for genetic accommodation. *Evolution* 68:656–672.
- Schluter, D. 2000. *The ecology of adaptive radiation*. Oxford University Press, Oxford.
- Schmidt, D. N., E. J. Rayfield, A. Cocking, and F. Marone. 2013. Linking evolution and development: synchrotron radiation X-ray tomographic microscopy of planktic foraminifers. *Palaeontology* 56:741–749.
- Schoch, R. R. 2014. Life cycles, plasticity and palaeoecology in temnospondyl amphibians. *Palaeontology* 57:517–529.
- Simpson, G. G. 1953. The Baldwin effect. *Evolution* 7:110–117.
- Slater, G. J., G. D. Yocum, and J. H. Bowsler. 2020. Diet quantity influences caste determination in honeybees. *Proceedings of the Royal Society of London B* 287:1–10.
- Spezzerferri, S., M. Kucera, P. N. Pearson, B. S. Wade, S. Rappo, C. R. Poole, R. Morard, and C. Stalder. 2015. Fossil and genetic evidence for the polyphyletic nature of the planktonic foraminifera “*Globigerinoides*”, and description of the new genus *Trilobatus*. *PLoS ONE* 10:e0128108.
- Stearns, B. P., and S. C. Stearns. 1999. *Watching from the edge of extinction*. Yale University Press, New Haven, Conn.
- Suzuki, Y., and H. F. Nijhout. 2006. Evolution of a polyphenism by genetic accommodation. *Science* 311:650–652.
- Taylor, P. D. 1990. Allele-frequency change in a class-structured population. *American Naturalist* 135:95–106.
- Trueman, C. N., M. T. Chung, and D. Shores. 2016. Ecogeochemistry potential in deep time biodiversity illustrated using a modern deep-water case study. *Philosophical Transactions of the Royal Society of London B* 371:1–10.
- Vanadzina, K., and D. N. Schmidt. 2021. Developmental change during a speciation event: evidence from planktic foraminifera. *Paleobiology* 48:120–136.
- Waddington, C. H. 1953. Genetic assimilation of an acquired character. *Evolution* 7:118–126.
- West-Eberhard, M. J. 2003. *Developmental plasticity and evolution*. Oxford University Press, New York.
- West-Eberhard, M. J. 2005. Developmental plasticity and the origin of species differences. *Proceedings of the National Academy of Sciences USA* 102(Suppl. 1):6543–6549.
- West-Eberhard, M. J. 2008. Toward a modern revival of Darwin's theory of evolutionary novelty. *Philosophy of Science* 75:899–908.
- Whittington, H. B. 1957. The ontogeny of trilobites. *Biological Reviews* 32:421–467.
- Zheng, J., J. L. Payne, and A. Wagner. 2019. Cryptic genetic variation accelerates evolution by opening access to diverse adaptive peaks. *Science* 365:347–353.