Interrelating Concepts from Genetics and Evolution: Why are Cod Shrinking?

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Abstract

Understanding evolutionary change requires an integrated understanding of genetics and evolution, as well as interrelating concepts from different levels of biological organization. However, students' knowledge about genetics and evolution often remains compartmentalized, and students struggle with thinking across levels. Thus, we present a classroom simulation of how selection affects both phenotypes and genotypes, which helps students distinguish between different levels of biological organization (i.e., phenotype and genotype) and track changes in phenotypes to changes in allele frequencies.

Key Words: *evolutionary change; phenotype; genotype; allele frequencies; genetics and evolution.*

○ Introduction

As evolution is the organizing principle and the unifying theme in biology, understanding evolutionary phenomena requires a thorough understanding of concepts from several disciplines. Recently, biology educators have emphasized the importance of an integrated understanding of genetics and evolution (e.g., Jördens et al., 2016; White et al., 2013b; Mead & Scott, 2010; Smith et al., 2009; Mayr, 2001). Evidence for this argument comes from biology education research, as students' knowledge of genetics and evolution has been documented to remain compartmentalized (e.g., Halldén, 1988; Ferrari & Chi, 1998; Shtulman, 2006). Halldén (1988, p. 545), for example, described the fact that students, when asked to explain how hereditary characteristics undergo change over time, lacked "a coherent picture of the mechanisms of genetics and their relationship to evolution." They were thus unable to see concepts from genetics and evolution as an interrelated whole.

Recently, biology educators have emphasized the importance of an integrated understanding of genetics and evolution.

Strengthening the genetic underpinnings of evolution, educators have focused on the interrelationships between genotype and phenotype at the molecular and cellular level. White, Heidemann, Loh, and Smith (2013a, p. 2) criticize that the teaching and learning of evolution is often focused "on variation and selection at a conceptual level. Thus, students tend to think of evolution as being relevant only to the macroscopic world, with little or no connection to what happens inside cells." Thus, molecular mechanisms are often given insufficient attention. To provide students with a better overall understanding of evolution, they recommend that teachers use so-called integrative cases, which "track the evolution from molecular genetics to the array of population phenotypes" (White et al., 2013b, p. 586). Biological examples displaying well-defined "genes to proteins to selectable phenotypes" pathways (p. 587) are expected to help students in their struggle to see interrelationships between genetics and evolution.

Symptomatically, considerable numbers of students tend to explain phenomena of evolutionary change at the phenotypic level alone. In a recent study conducted by the authors of this paper, approximately 30 percent of the sample of the high school students failed to integrate genetic knowledge into their explanations of evolutionary change (Jördens et al., 2016). This is a surprising finding, since the students had been proven to possess genetic knowledge from a course taught prior to the study.

Two examples follow: One student explained the evolutionary impact of trophy hunting on the tusk length of African Elephants in the following way:

> Because male elephants with long tusks are killed very often, there are only bulls with smaller tusks. Females mate with these bulls, as there are fewer and fewer bulls with long tusks. That's

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> why male offspring also have smaller tusks. Thus, tusk size becomes smaller because of hunting. (Jördens et al., 2016, p. 970)

Another 20 percent of the students made unspecific references to concepts at the genetic level in order to explain evolutionary change, for example:

> Because elephants with long tusks are hunting trophies, they are shot more frequently than elephants with short tusks. As a consequence, bulls with shorter tusks make up for a greater part of the gene pool and therefore bulls with shorter tusks predominate when the number of elephants with longer tusks decreases. (Jördens et al., 2016, p. 970)

As the first student explanation is purely phenotypic and the second does not address changes in allele frequencies, educators should be challenged to encourage students' thinking across levels and establish links between concepts at different levels of organization, i.e., to promote vertical coherence of concepts in explanations (e.g., Verhoeff, 2003; White et al., 2013a).

Thus, the aim of this paper is to present a classroom simulation, which we used in our research and which proved effective in showing to the students how selection affects both phenotypes and genotypes. It focuses on changes in allele frequencies that, as such, are key to understanding phenomena of evolutionary change. The simulation provides opportunities for integrating concepts from evolution (e.g., artificial selection) and genetics (e.g., polygenic inheritance) as well as for interrelating concepts at different levels of biological organization. Because students struggle with these problems, we recommend biology teachers to use this simulation.

○ Simulating Evolutionary Change in the Classroom

Simulations developed for classroom use come in many forms, e.g., computer simulations and hands-on simulations involving card games and board games. They are beneficial in several ways: Simulation are generally perceived as interesting and motivating by the students (e.g., Gelbart & Yarden, 2006; Blake & Scanlon, 2007). Furthermore, they improve understanding (e.g., Randel et al., 1992; Christensen-Dalsgaard & Kanneworff, 2009), encourage self-directed learning (e.g., Grüne-Yanoff & Weirich, 2010), and promote conceptual change (e.g., Abraham et al., 2009; Blake & Scanlon, 2007). Moreover, educational simulations, if well-made, present biological phenomena in a clear and illustrative way (e.g., Christensen-Dalsgaard & Kanneworff, 2009).

Based on the observation that many students tend to explain evolutionary change at the phenotypic level alone and fail to integrate genetic knowledge into their explanations of evolutionary change, the authors of this paper reviewed classroom simulations on the impact of selection on evolutionary change (Jördens et al., 2016). The review revealed differences in the ways in which different levels of biological organization are addressed. Whereas some simulations show how natural selection affects phenotypes alone (Figure 1; e.g., Stebbins & Allen, 1975; Scheersoi & Kullmann, 2007; Lauer, 2000; Maret & Rissing, 1998), other simulations demonstrate that natural selection results in changes of both phenotypes and allele frequencies (Figure 2; e.g., Jördens et al., 2016; Christensen-Dalsgaard & Kanneworf, 2009; Frey et al., 2010; Fifield & Fall, 1992).

Contrasting the two types of simulations in a randomized controlled trial, the authors of this paper provided evidence that simulations, which use an integrative approach by explicitly addressing different levels of biological organization (see Figure 2), help students understand how selection affects both phenotypes and allele frequencies (Jördens et al., 2016). In contrast, simulations that focus on the phenotypic level alone prompt students to continue to provide post-test explanations that remain at the phenotypical level and lack in genetic aspects.

Figure 1. Traditional simulation of natural selection, focusing on phenotypic change alone (e.g., Stebbins & Allen, 1975). Differently adapted organisms are represented by colored chips spread out over a piece of fabric, which represents the habitat.

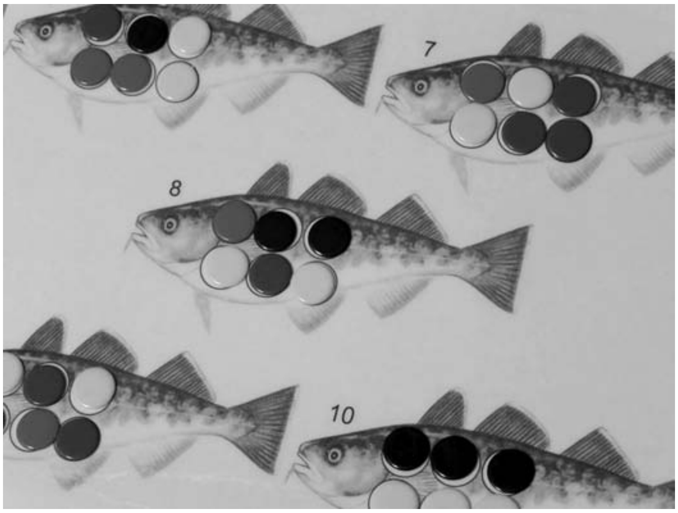


Figure 2. New simulation, described in this paper, focusing on both phenotypic change (shrinking body size of Atlantic cod) and changes in allele frequencies due to size-selective harvesting (www.evolution-of-life.com and Jördens et al., 2016).

○ Description of "Why Are Cod Shrinking?"

General Design Principles

The simulation is based on a learning activity by Allen and Wold (2009) and deals with an authentic example of artificial selection, the shrinking of Atlantic cod from size-selective harvesting. In terms of general design principles, the simulation (1) represents concepts at different levels of biological organization as different entities and (2) encourages students to interrelate concepts by ascending and descending between the different levels of biological organization. The latter is also called the Yo-Yo learning and teaching strategy (Knippels, 2002). Use is made of different representations for organisms (drawings of Atlantic cod) and alleles (colored chips). This is an important point also in light of the student misconception that traits—rather than genes—are passed on from one generation to the next (Lewis & Kattmann, 2004; Marbach-Ad & Stavy, 2000). In the simulation, a distinction is made between impacts on phenotypes and genotypes, which marks a significant contrast to a similar simulation by Allen and Wold (2009), in which no representational distinction is made between organisms and alleles. The second design principle is put into practice by asking students—after each round of selection—to register body size for each individual, mean body size for the population, and frequencies for each of the four alleles used to represent polygenic inheritance of body size. Thus, as a result of three rounds of artificial selection, students see how selection affects both phenotypes (shrinking body size) and genotypes (changes in allele frequencies). In particular, alleles contributing to a small body size become more frequent, whereas alleles contributing to large body size become less frequent.

After the simulation, biology teachers should focus on the details of polygenic inheritance, because another important characteristic of the simulation is its focus on a quantitative trait (body size), i.e., a multitude of genes contribute to the development of size (additive genetic variance). This is in contrast to many common learning activities, which use qualitative traits, i.e., few or single genes contribute to a (distinct) phenotype (e.g., Stebbins & Allen, 1975; Fifield & Fall, 1992). Researchers have argued for including more examples of polygenic inheritance, as "there are actually many more polygenic and multifactorial . . . conditions" (Tsui & Treagust, 2010, p. 1091) than the rather rare examples of qualitative (monogenic) traits.

Materials and Instructions

The following materials are required for each group of up to five students:

- a playing board (see Figure 3)
- student worksheets (see Figure 4).

All materials are available in English, German, and French for download at www.evolution-of-life.com, which also includes additional materials, in particular biological background information and teaching advice.

For each group, the following materials should be prepared separately:

- a non-transparent bag for the playing chips (the genepool) (such as a linen bag)

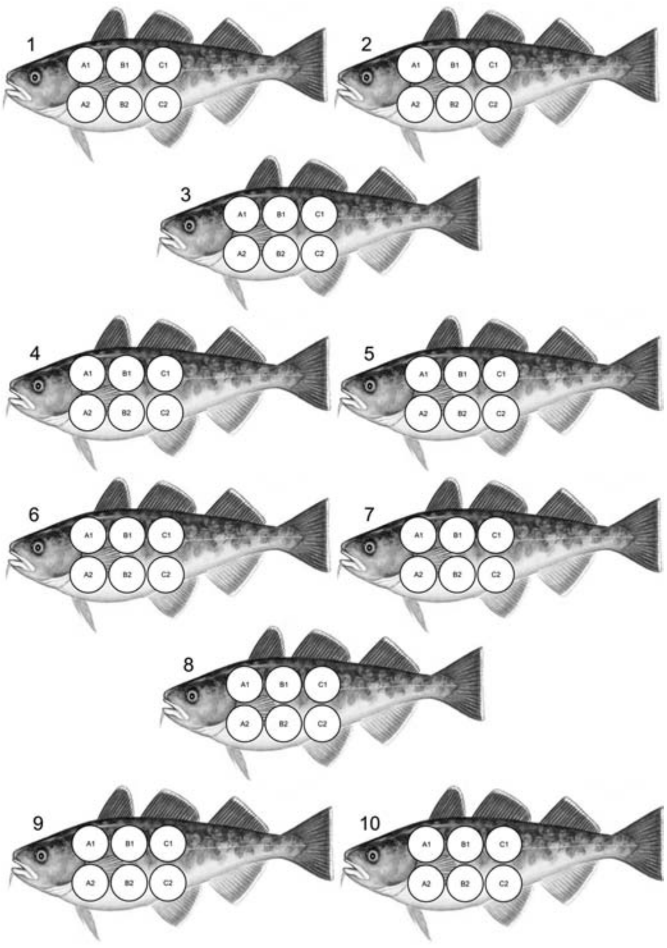


Figure 3. The playing board represents a population of ten cod individuals (available at www.evolution-of-life.com).

- playing chips (alleles), diameter ca. 15mm. For each group of up to five students, 60 chips of four different colours are necessary, for example: 60 red, 60 yellow, 60 black, 60 blue. As an alternative to playing chips, one might use colored chocolate candies.

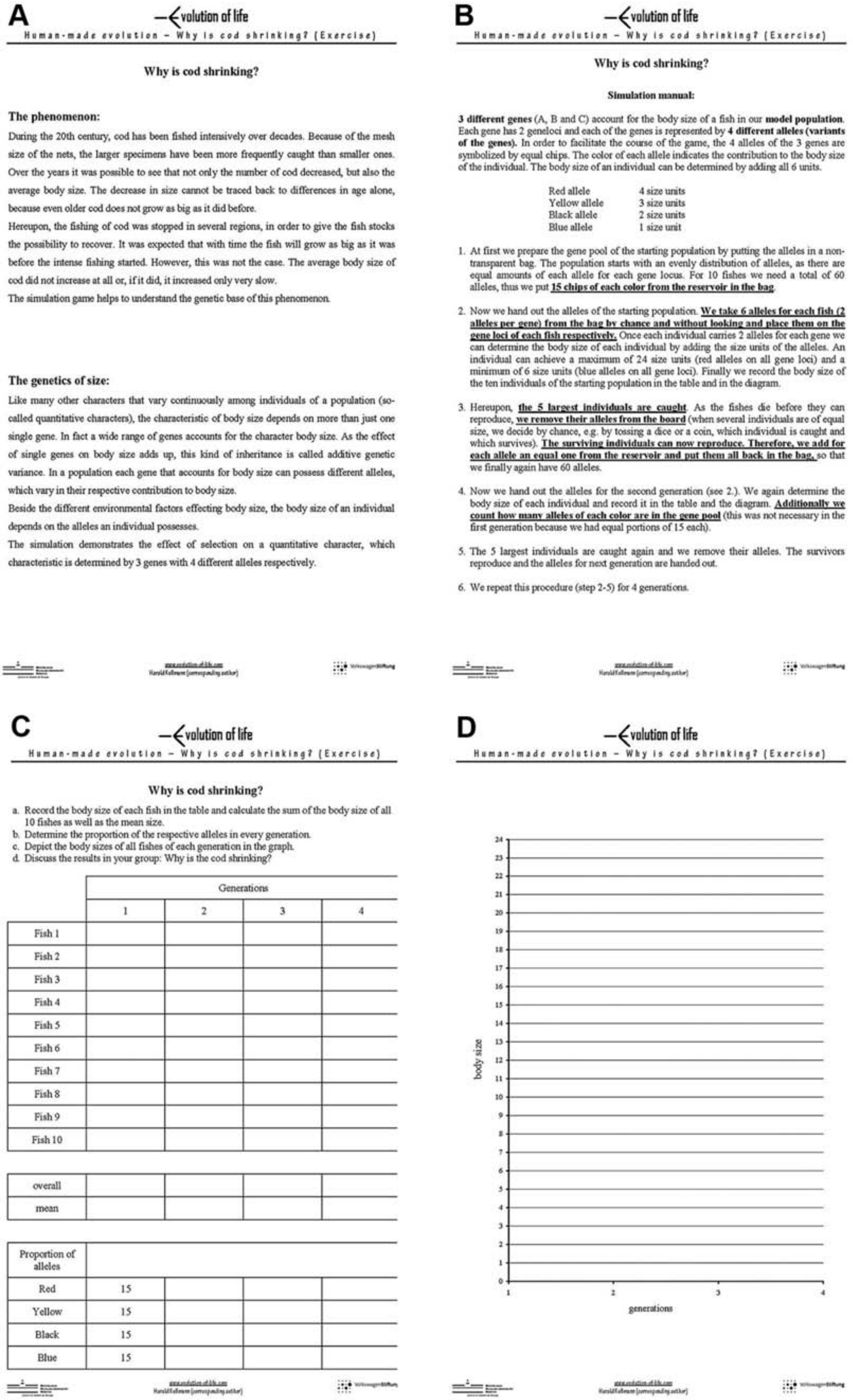
○ Procedures

General Requirements

Teachers are recommended to use the simulation after having introduced basic concepts from genetics and evolution. As the simulation provides the opportunity to teach polygenic inheritance, students must be familiar with terms like "genes" and "alleles," and have a firm working understanding of Mendelian genetics. This is necessary for understanding the differences between monogenic and polygenic inheritance. Students, also, should be familiar with basic evolutionary concepts. As "Why is cod shrinking?" deals with artificial selection, it can be placed at the beginning of an evolutionary teaching unit after having introduced the concepts of species and genepool, as well as mutation and sexual recombination as sources of genetic variation.

Preparing the Simulation (15 min.)

Prior to conducting the simulation, the students should be encouraged to read the description of the authentic phenomenon on the



A

—Evolution of life

Human-made evolution – Why is cod shrinking? (Exercise)

Why is cod shrinking?

The phenomenon:

During the 20th century, cod has been fished intensively over decades. Because of the mesh size of the nets, the larger specimens have been more frequently caught than smaller ones. Over the years it was possible to see that not only the number of cod decreased, but also the average body size. The decrease in size cannot be traced back to differences in age alone, because even older cod does not grow as big as it did before.

Hereupon, the fishing of cod was stopped in several regions, in order to give the fish stocks the possibility to recover. It was expected that with time the fish will grow as big as it was before the intense fishing started. However, this was not the case. The average body size of cod did not increase at all or, if it did, it increased only very slow.

The simulation game helps to understand the genetic base of this phenomenon.

The genetics of size:

Like many other characters that vary continuously among individuals of a population (so-called quantitative characters), the characteristic of body size depends on more than just one single gene. In fact a wide range of genes accounts for the character body size. As the effect of single genes on body size adds up, this kind of inheritance is called additive genetic variance. In a population each gene that accounts for body size can possess different alleles, which vary in their respective contribution to body size.

Beside the different environmental factors effecting body size, the body size of an individual depends on the alleles an individual possesses.

The simulation demonstrates the effect of selection on a quantitative character, which characteristic is determined by 3 genes with 4 different alleles respectively.

B

—Evolution of life

Human-made evolution – Why is cod shrinking? (Exercise)

Why is cod shrinking?

Simulation manual:

3 different genes (A, B and C) account for the body size of a fish in our **model population**. Each gene has 2 geneloci and each of the genes is represented by **4 different alleles (variants of the genes).** In order to facilitate the course of the game, the 4 alleles of the 3 genes are symbolized by equal chips. The color of each allele indicates the contribution to the body size of the individual. The body size of an individual can be determined by adding all 6 units.

Red allele	4 size units
Yellow allele	3 size units
Black allele	2 size units
Blue allele	1 size unit

1. At first we prepare the gene pool of the starting population by putting the alleles in a non-transparent bag. The population starts with an evenly distribution of alleles, as there are equal amounts of each allele for each gene locus. For 10 fishes we need a total of 60 alleles, thus we put **15 chips of each color from the reservoir in the bag**.
2. Now we hand out the alleles of the starting population. **We take 6 alleles for each fish (2 alleles per gene) from the bag by chance and without looking and place them on the gene loci of each fish respectively.** Once each individual carries 2 alleles for each gene we can determine the body size of each individual by adding the size units of the alleles. An individual can achieve a maximum of 24 size units (red alleles on all gene loci) and a minimum of 6 size units (blue alleles on all gene loci). Finally we record the body size of the ten individuals of the starting population in the table and in the diagram.
3. Hereupon, **the 5 largest individuals are caught**. As the fishes die before they can reproduce, **we remove their alleles from the board** (when several individuals are of equal size, we decide by chance, e.g. by tossing a dice or a coin, which individual is caught and which survives). **The surviving individuals can now reproduce. Therefore, we add for each allele an equal one from the reservoir and put them all back in the bag,** so that we finally again have 60 alleles.
4. Now we hand out the alleles for the second generation (see 2.). We again determine the body size of each individual and record it in the table and the diagram. **Additionally we count how many alleles of each color are in the gene pool** (this was not necessary in the first generation because we had equal portions of 15 each).
5. The 5 largest individuals are caught again and we remove their alleles. The survivors reproduce and the alleles for next generation are handed out.
6. We repeat this procedure (step 2-5) for 4 generations.

C

—Evolution of life

Human-made evolution – Why is cod shrinking? (Exercise)

Why is cod shrinking?

a. Record the body size of each fish in the table and calculate the sum of the body size of all 10 fishes as well as the mean size.
b. Determine the proportion of the respective alleles in every generation.
c. Depict the body sizes of all fishes of each generation in the graph.
d. Discuss the results in your group: Why is the cod shrinking?

	Generations			
	1	2	3	4
Fish 1				
Fish 2				
Fish 3				
Fish 4				
Fish 5				
Fish 6				
Fish 7				
Fish 8				
Fish 9				
Fish 10				

overall				
mean				

Proportion of alleles				
Red	15			
Yellow	15			
Black	15			
Blue	15			

D

—Evolution of life

Human-made evolution – Why is cod shrinking? (Exercise)

Figure 4. The student worksheets include **(A)** a description of the phenomenon, **(B)** a simulation manual, **(C)** a table (for recording body sizes and allele frequencies), and **(D)** a diagram (for recording body size) for documenting the impact of artificial selection on phenotypes and genotypes (available at www.evolution-of-life.com).

students' worksheet and explain the causes of the phenomenon. This activates prior understanding. Student explanations often reveal typical misconceptions as well as learning difficulties, like confusion of levels (e.g., inheritance of traits rather than genes) and disconnect between levels (e.g., students who explain evolutionary change at the phenotypic level alone). One student's explanation before the simulation is:

> The body size of cod has decreased in the last 60 years because, due to intense fishery, the fish adapted to the circumstances. Now they are small and can't be caught by the nets so well or can even swim out of the nets. I think, after the fishery stopped, the average body size of cod did not increase, so that the fish can protect themselves from these threats in the next generations. The fish had no reason to adapt to the old conditions.

As this quote illustrates, students tend to explain evolutionary change at the phenotypic level alone (disconnect between levels), which is problematic in itself and represents a specific starting point for this teaching recommendation. At the start of the teaching unit, a documentary film, *The case of the shrinking cod* (ca. 8 min., www.evolution-of-life.com) is recommended as an introduction to the topic.

Doing the Simulation (45–60 min.)

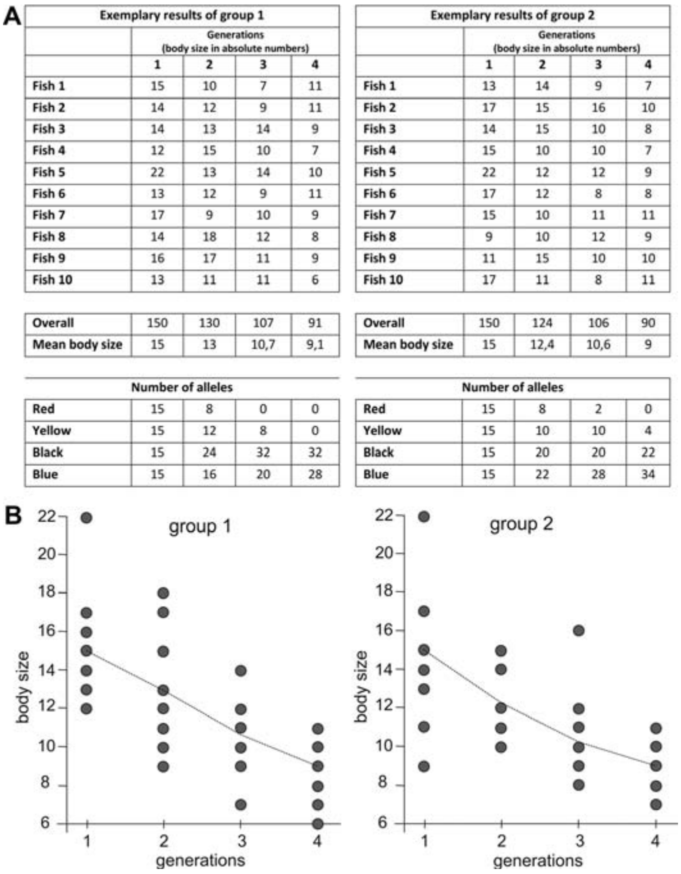
For the simulation, splitting up the class into small groups of up to five students is recommended. At the beginning, teachers hand out the worksheets to the students (see Figure 4 A–D, available at www.evolution-of-life.com). The worksheets consist of a short description of the phenomenon and a detailed simulation manual, as well as a table and a diagram for recording the results of the simulation

Step 1. First, the students prepare the gene pool of the starting population by putting a total of 60 alleles (equal amount of each of alleles: 15 chips of each color) in a non-transparent bag. The remaining chips of each color provide a reserve for the next generations.

Step 2. The simulation starts with filling the gene loci with alleles (chips) by chance; i.e., students draw six alleles per fish from the bag without looking inside. As a next step, students calculate the body size for each individual in absolute numbers, as each of the four types of alleles contributes differently to body size (the "size value" of each type of allele is noted in the simulation manual, see Figure 4B). For each of the ten individuals of the starting population, body size is recorded in the table and in the diagram of the worksheets (see Figure 4; for sample results, see Figure 5). Students also calculate the mean body size for the population and record allele frequencies for all four types of alleles in the table. To provide orientation for students who are expected to record data, allele frequencies for the starting population (generation 1) are noted in the table (see Figure 4C).

Step 3. Simulating artificial selection, the five biggest fish are "caught" and their alleles are removed from the genepool of the population. The surviving fish reproduce, and their alleles are doubled in number by taking alleles from the reserve so that the genepool (the nontransparent bag) contains 60 alleles again.

Step 4. Steps 1, 2, and 3—allotting alleles to gene loci by chance, calculating body size, counting allele frequencies, recording data, and catching the five biggest fish—are repeated three times. Sample results for body size and the change of allele frequencies can be seen in Figure 5.



Exemplary results of group 1				
	Generations (body size in absolute numbers)			
	1	2	3	4
Fish 1	15	10	7	11
Fish 2	14	12	9	11
Fish 3	14	13	14	9
Fish 4	12	15	10	7
Fish 5	22	13	14	10
Fish 6	13	12	9	11
Fish 7	17	9	10	9
Fish 8	14	18	12	8
Fish 9	16	17	11	9
Fish 10	13	11	11	6

Overall	150	130	107	91
Mean body size	15	13	10,7	9,1

Number of alleles				
Red	15	8	0	0
Yellow	15	12	8	0
Black	15	24	32	32
Blue	15	16	20	28

Exemplary results of group 2				
	Generations (body size in absolute numbers)			
	1	2	3	4
Fish 1	13	14	9	7
Fish 2	17	15	16	10
Fish 3	14	15	10	8
Fish 4	15	10	10	7
Fish 5	22	12	12	9
Fish 6	17	12	8	8
Fish 7	15	10	11	11
Fish 8	9	10	12	9
Fish 9	11	15	10	10
Fish 10	17	11	8	11

Overall	150	124	106	90
Mean body size	15	12,4	10,6	9

Number of alleles				
Red	15	8	2	0
Yellow	15	10	10	4
Black	15	20	20	22
Blue	15	22	28	34

Figure 5. Exemplary results from two groups of students are presented in the tables **(A)** and in the diagrams **(B)**. Lines represent mean body size per generation over time.

The students are given the following tasks in writing (see worksheet Figure 4C, available at www.evolution-of-life.com):

- Record the body size of each fish in the table, and calculate the sum of the body size of all ten fish as well as the mean size.
- Determine the proportion of the respective alleles in every generation.
- Present the body sizes of all fish of each generation in the graph.
- Discuss the results in your group: Why is cod shrinking?

Conclusions

The simulation presented in this paper provides students the opportunity to develop an integrated understanding of evolutionary change. In particular, biology educators can expect students to

- distinguish between phenotype (body size of cod) and genotype (allele frequencies)
- think back and forth between levels and interrelate concepts at different levels, in particular, track changes in phenotype to changes in genotype over several generations
- explain the long-term consequences of size-selective harvesting, and
- develop a sophisticated understanding of artificial selection and evolution.

Furthermore, teachers can expect a decreasing number of students who explain evolutionary change at the phenotypical level alone. In a related study, the number of students decreased from 30 percent in the pre-test to 7 percent in the post-test after engaging in the simulation (Jördens et al., 2016). Conversely, the number of students explaining evolutionary change with reference to changes in allele frequencies increased from 48 percent in the pre-test to 88 percent in the post-test. Nevertheless, although the simulation is based on self-directed learning, we recommend that teachers—after the simulation—explicitly address the impact of selection on phenotypes and genotypes in order to support weaker students' understanding of how allele frequencies are impacted by selection.

Table 1. Sample assessment tasks. (A) reproduction task and (B) transfer task.

(A) Size-selective harvesting of Atlantic cod	(B) Trophy hunting of Asian elephants
During the 20th century, cod has been intensively fished over decades in the northeast Atlantic. Because of the mesh size of the nets, larger fish have been more frequently caught than smaller ones. Over the last 60 years, this resulted in declining numbers of cod as well as smaller cod, whose average body size decreased from 95 cm to 65 cm. Explain in as much detail as possible, how cod fishing caused the body size of cod to decrease. After cod fishing was stopped, the average body size of cod did not increase at all, or if it did, it increased only very slowly. Explain causes for this phenomenon as much detail as possible.	Tusks of Asian bull elephants are an important characteristic for finding a mate. Elephant cows prefer bulls with long tusks because they signal strength and health. Moreover bulls with long tusks have advantages in rival fights. However, the average length of Asian elephant tusks have decreased in recent decades. Trophy hunting was held accountable for this phenomenon. Explain in as much detail as possible, how trophy hunting caused tusk length to decrease. After trophy hunting and poaching were prohibited, the average tusk length did not increase at all, or if it did, it increased only very slowly. Explain causes for this phenomenon in as much detail as possible.

○ Assessment

The students' ability to explain the impact of artificial selection on phenotypes and genotypes can be tested by using reproduction and transfer tasks (Table 1).

One student explained his improved understanding of the reproductive task (Table 1A) in the following way:

> Cod has several genes which contribute to body size . . . By catching the big fish, alleles are removed which are crucial for body size. Therefore, the next generations of fish are smaller. [After fishery was stopped, cod did not grow because] it is the alleles, which are responsible for body size, which allow for small fish only. In the population, there are no alleles which can be found in big fish so that these genes cannot be passed on. (Jördens et al., 2016, p. 970)

Furthermore, a good post-activity exercise to assess the students' ability to interrelate and to apply their genetic and evolutionary knowledge is to have students discuss, for example:

- consequences of different types of artificial selection (e.g., breeding, fishery or trophy hunting) for population dynamics and ecosystems
- ethical aspects concerning the responsibility of humans for this evolutionary phenomenon.

Group discussions can also easily be replaced or complemented by poster presentations.

○ Acknowledgments

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