D4.1 Natural selection

Continuity and change—Ecosystems

Standard level and higher level: 2 hours

Additional higher level: 2 hours

Guiding questions

• What processes can cause changes in allele frequencies within a population?

• What is the role of reproduction in the process of natural selection?

SL and HL

D4.1.1—Natural selection as the mechanism driving evolutionary change
Students should appreciate that natural selection operates continuously and over billions of years, resulting in the biodiversity of life on Earth.

- **Selection** is a non-random evolutionary mechanism by which **specific** alleles linked to **beneficial phenotypes** become more common within the population across time
  - Different types of selection are classified according to what causes selection to occur:
    - **Natural selection** occurs when the natural environment selects for beneficial phenotypes
    - **Artificial selection** occurs when humans select for phenotypes that serve human needs & wants
    - **Sexual selection** occurs when the opposite sex selects for phenotypes that improve mating success & reproduction
- **Natural selection** is the main (but not only) mechanism of evolutionary change, and requires:
  1. **Variation**: individuals must express distinct phenotypes
  2. **Heritability**: the phenotypes affecting survival and reproduction must have a genetic basis in order to be passed down to offspring
  3. **Differential fitness**: the phenotypes must have different survival and reproductive values (i.e. varying levels of fitness)
- Natural selection operates continuously because organisms live in environments that are constantly changing
  - Organisms gradually evolve differences due to selection over billions of years, leading to speciation and resulting in the biodiversity of life on Earth

D4.1.2—Roles of mutation and sexual reproduction in generating the variation on which natural selection acts

Mutation generates new alleles and sexual reproduction generates new combinations of alleles.

- **Genetic variation** is the differences in DNA sequences between individuals within a population
- **Phenotypic variation** is the differences in the observable traits (phenotypes) of individuals, which is determined by the genetic makeup of the organism and its environment
- The **amount** and **type** of genetic variation determines how much adaptation can occur in a population
  - The greater the amount of genetic variation (e.g. genes have many alleles), the higher the chance that one of the alleles can be beneficial (& thus selected for)
  - The greater the amount of beneficial genetic variation, the more evolutionary change the population will experience due to natural selection
    - If most of the genetic variation is neutral (i.e. does not affect fitness), the adaptability of the population will not be high because natural selection only acts when differential fitness exists
- There are several mechanisms that generate genetic variation (& thus raw material for selection):
  - **Mutations** generate **new alleles**
    - In **asexually** reproducing organisms, all mutations are inherited by the offspring
    - In **sexually** reproducing organisms, only mutations in germline cells (cells that produce gametes) are inherited by the offspring
    - Mutations are random in the sense that they occur regardless of their fitness value, but natural selection is not random because it only makes beneficial mutations more common
  - **Sexual reproduction** generates new **combinations** of alleles (but NOT new alleles)
    - **Crossing over** in prophase I mixes paternal and maternal alleles to produce chromosomes with different alleles
    - **Independent assortment** in metaphase I randomly aligns homologous chromosomes, so alleles on different chromosomes are distributed into gametes in different combinations
    - **Fertilization** produces zygotes with unique allele combinations since millions of distinct sperm can fertilize one egg

D4.1.3—Overproduction of offspring and competition for resources as factors that promote natural selection
Include examples of food and other resources that may limit carrying capacity.

- **Selection pressures** are **biotic** or **abiotic** agents that make some phenotypes more likely to survive & reproduce than others
  - This promotes natural selection because it creates differential fitness within the population
- Biotic selection pressures are often **density-dependent factors** that depend on the size or density of the population of interest, for example:
  - **Overproduction of offspring** (resulting in large population densities) leads to **intraspecific competition** for limited resources, promoting natural selection
  - **Interspecific competition** (between species) for limited resources also promote natural selection
  - **Disease outbreak** promotes natural selection in dense populations (as disease can spread faster)
  - **Predation** promotes natural selection of individuals that can evade or survive predators
- Density-dependent selection pressures often lead to logistic patterns of growth that limit the carrying capacity of a population

D4.1.4—Abiotic factors as selection pressures
Include examples of density-independent factors such as high or low temperatures that may affect survival of individuals in a population.

- Abiotic selection pressures are often **density-independent factors** that do **NOT** depend on population size or density to promote natural selection:
  - For example, high or low temperatures may affect survival (& thus reproduction) of individuals in a population, which promotes selection
  - Other examples include natural disasters, precipitation patterns, & altitude

D4.1.5—Differences between individuals in adaptation, survival and reproduction as the basis for natural selection
Students are required to study natural selection due to intraspecific competition, including the concept of fitness when discussing the survival value and reproductive potential of a genotype.

- **Fitness** refers to the survival value and reproductive potential of a genotype
  - Genotypes that produce beneficial phenotypes have greater fitness because they make individuals that possess them more likely to survive & reproduce
- **Differential fitness** between individuals (differences in fitness, i.e. differences in adaptation, survival, & reproduction) is the basis for natural selection
  - Phenotypic variation without variation in fitness does not promote natural selection
- **Intraspecific competition** (competition between individuals of the same species) is an important selection pressure that drives natural selection in populations

D4.1.6—Requirement that traits are heritable for evolutionary change to occur

Students should understand that characteristics acquired during an individual's life due to environmental factors are not encoded in the base sequence of genes and so are not heritable.

- Natural selection acts on **heritable phenotypic variants** of a population that improve survival (& thus likelihood of reproduction)
  - If the beneficial phenotypic variants have a specific genetic component, the gene variants responsible for this beneficial phenotype will increase in frequency within the population
  - Phenotypic variation that cannot be inherited (i.e. characteristics acquired during an individual's life due to environmental factors, like a muscular body due to regular exercise) cannot be operated on by natural selection
- **Additional higher level**: although epigenetic tags could be inherited in gametes and thus passed to offspring (gene imprinting), they do not change DNA sequences and thus far are not regarded as having a role in evolutionary change.

NOS: In Darwin's time it was widely understood that species evolved, but the mechanism was not clear. Darwin's theory provided a convincing mechanism and replaced Lamarckism. This is an example of a paradigm shift. Students should understand the meaning of the term "paradigm shift".

A **paradigm shift** is a fundamental change in the basic concepts and approaches in a scientific discipline. Lamarckism was a previously accepted evolutionary theory until Darwinism provided more a more convincing mechanism of evolution, leading to a paradigm shift in biology.

D4.1.7—Sexual selection as a selection pressure in animal species

Differences in physical and behavioural traits, which can be used as signs of overall fitness, can affect success in attracting a mate and so drive the evolution of an animal population. Illustrate this using suitable examples such as the evolution of the plumage of birds of paradise.

- **Sexual selection** occurs when the opposite sex selects for phenotypes that improve **mating success** & **reproduction**
  - Differences in physical and behavioural traits (with a genetic basis) between individuals of one sex are used as **indicators** of overall fitness for the other sex
  - The phenotypic traits may not always improve survival of individuals, but they can be sexually selected for if they offset an individual's diminished survival with an increase in their reproduction
    - For many species, these sexual traits do not help the organism adapt to its environment, and expediate quite a lot of energy despite selection being responsible for their development
    - Sexual selection 'stops' only when the trait becomes so exaggerated that any further increase reduces an individual's survival more than it attracts mates, so that their net production of offspring suffers
- Sexual selection involves one sex **choosing** the phenotypic traits and the other sex **competing** with other individuals (of the same sex) for mating
  - In some sexual systems, males compete with each other to mate with females, in which case sexual selection will favor three types of genes:
    - Genes for a male "indicator" trait reflecting that he has good genes
    - 'Good' genes in males whose presence is reflected by the indicator
    - Genes that make a female prefer that indicator trait
  - Other sexual systems where females compete with each other to mate with males also exist
- In birds of paradise, male birds have colorful plumage which indicates to the females that they are healthy & possess good genes for their offspring

D4.1.8—Modelling of sexual and natural selection based on experimental control of selection pressures
Application of skills: Students should interpret data from John Endler's experiments with guppies.

- **John Endler** modelled the effects of natural & sexual selection through guppies, a type of fish:
  - Male guppies can either have colorful or dull skin
    - Colorful skin is preferred by females & thus favored by sexual selection
    - Dull skin is better for camouflage & thus favored by natural selection
  - The strength of each opposing selection pressure (female choice vs predation) determines the dominant skin phenotype in guppy populations
    - When predation is low, female choice becomes the dominant selection pressure & male guppies with more colorful skin become more common (sexual selection is stronger than natural selection)
    - When predation is high it becomes the dominant selection pressure & male guppies with dull skin become more common (natural selection is stronger than sexual selection)

Additional higher level

D4.1.9—Concept of the gene pool
A gene pool consists of all the genes and their different alleles, present in a population.

- A **gene pool** consists of all the genes and their different **alleles** present in a **population**
- Populations evolve when **allele frequencies** of their gene pools change due to random or non-random mechanisms of evolutionary change

D4.1.10—Allele frequencies of geographically isolated populations
Application of skills: Students should use databases to search allele frequencies. Use at least one human example.

- Species may exist in different geographically isolated environments and thus individuals may belong to different populations
  - Despite belonging to the same species, these populations have distinct gene pools with different allele frequencies
  - For example, the **lactase persistence allele** (enables lactose **tolerance**) in humans exists in different frequencies across populations
    - People living in certain continents or regions are more likely to be lactose intolerant than others

D4.1.11—Changes in allele frequency in the gene pool as a consequence of natural selection between individuals according to differences in their heritable traits

Darwin developed the theory of evolution by natural selection. Biologists subsequently integrated genetics with natural selection in what is now known as neo-Darwinism.

- Natural selection increases the frequency of beneficial alleles within the gene pool
    - As beneficial alleles become more common, deleterious alleles become rarer (selected against)
- Darwin developed the theory of evolution by natural selection but was unable to fully explain all its details (DNA was not known back then)
    - Biologists subsequently integrated new discoveries in genetics with natural selection to emerge with what is now known as **neo-Darwinism**

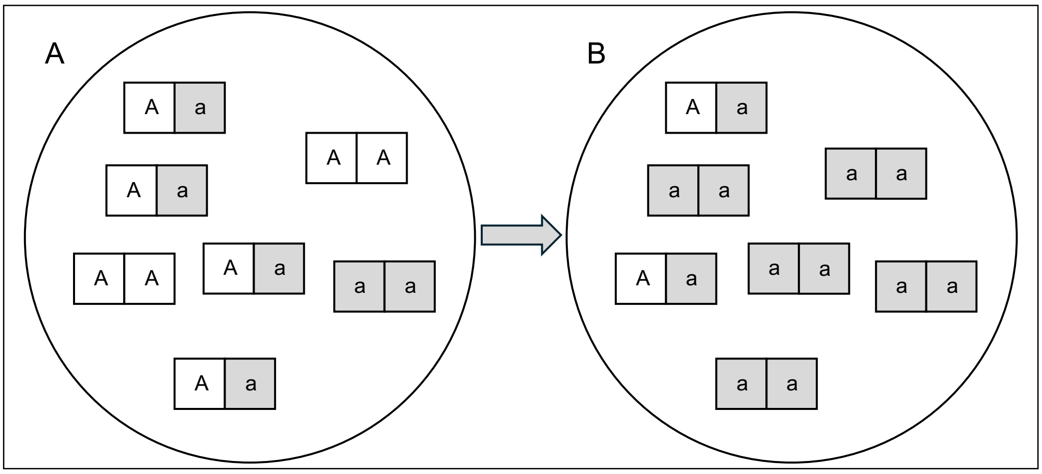

Figure 1: (a) gene pool before natural selection (b) gene pool after natural selection.

D4.1.12—Differences between directional, disruptive and stabilizing selection
Students should be aware that all three types result in a change in allele frequency.

- Natural selection affects the distribution of ***phenotypes*** in three main ways:

1. **Stabilizing selection**: the intermediate phenotype is chosen as the population stabilizes on a single trait, which decreases genetic diversity due to homogeneity

- (e.g. human birth weight is a type of stabilizing selection since heavy babies cause pregnancy complications and light babies are less likely to survive)

2. **Directional selection**: one of two phenotypic extremes within the spectrum is selected for, causing the allele frequency to continuously shift towards one 'direction'

- (e.g. during the industrial revolution, air pollution caused tree bark to turn into a black color, so black peppered moths were more likely to survive than white ones due to camouflage)

3. **Disruptive (diversifying) selection**: when two extreme/divergent phenotypes are favored over intermediate ones, increasing genetic diversity and heterogeneity

- (e.g. big male elephants can mate by brute force and small ones can sneak into the big males' territory and mate, whereas medium-sized elephants are too big to sneak in and too small to overtake the large elephants in a battle)

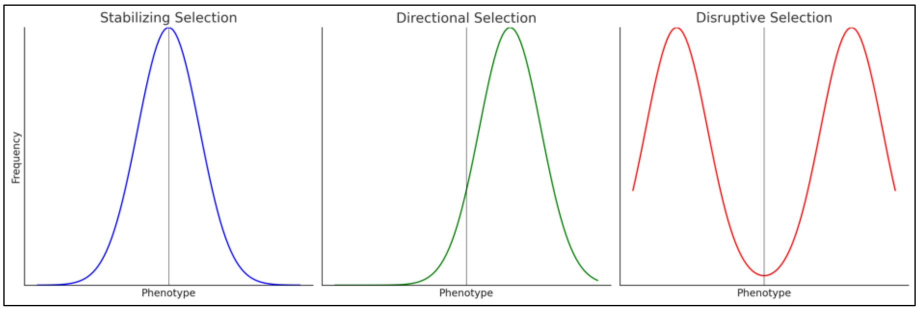

Figure 2: distribution of phenotype frequency in different types of natural selection.

D4.1.14—Hardy–Weinberg conditions that must be maintained for a population to be in genetic equilibrium
Students should understand that if genotype frequencies in a population do not fit the Hardy–Weinberg equation, this indicates that one or more of the conditions is not being met, for example mating is non-random or survival rates vary between genotypes.

- **Genetic equilibrium** is a condition in which the allele frequency within a gene pool does not change across generations, satisfying the following conditions:
  - No mutations (no alleles are introduced into the gene pool)
  - No gene flow (individuals (thus genes) do not enter or exit the population)
  - No natural selection
  - Random mating (individuals do not favor some characteristics over others)
  - Organisms are diploid and reproduce sexually
  - Population size is infinitely large (to reduce the effects of non-random evolutionary mechanisms on allele frequency)
- Genetic equilibrium can be attributed either to the entire genome or to one specific gene:
  - If the entire genome is considered, then these conditions have to be met for every gene
  - If one single gene is considered, then these criteria have to be met for that gene only
- The **Hardy-Weinberg Principle of Equilibrium** states that allele frequencies are inherently stable in populations as long as no evolutionary force (random or non-random) is acting on them
- While some genes *may* be at equilibrium, is it highly unlikely for a real population to have *all* of its genes at equilibrium
  - Even though no real population satisfies the Hardy-Weinberg equilibrium, it provides a baseline model to which we can compare actual populations to in order to detect how evolutionary forces are acting on the population’s gene pool

D4.1.13—Hardy–Weinberg equation and calculations of allele or genotype frequencies

Use *p* and *q* to denote the two allele frequencies. Students should understand that $p + q = 1$ so genotype frequencies are predicted by the Hardy–Weinberg equation: $p^2 + 2pq + q^2 = 1$.
If one of the genotype frequencies is known, the allele frequencies can be calculated using the same equations.

- **Allele frequency** is the proportion/fraction of a specific allele within a population
  - Number of individuals with a specific allele is **NOT** equal to allele frequency; in homozygous genotypes the allele is counted twice

$$\textbf{Allele frequency} = \frac{\textit{number of a specific allele within the population}}{\textit{total number of alleles at that locus in the population}}$$

- **Genotype frequency** is the proportion/fraction of a specific genotype within a population

$$\textbf{Genotype frequency} = \frac{\textit{number of individuals with a specific allele combination}}{\textit{total number of individuals in the population}}$$

- In genes with 2 alleles, the sum of all 3 genotype frequencies is equal to 1 (100%):

$$p^2 + 2pq + q^2 = 1$$

  - p^2 = homozygous genotype frequency for the *p* allele
  - $2pq$ = heterozygous genotype frequency
  - q^2 = homozygous genotype frequency for the *q* allele
- Scientists apply statistical tests using the Hardy–Weinberg equation to determine if a population is evolving
  - **Observed genotype frequency** is the **actual** count of each genotype physically counted in the real population (i.e. what scientists record when observing a real population)
  - **Expected genotype frequency** is the **theoretical** count of each genotype IF the population were to be at Hardy–Weinberg equilibrium (i.e. not evolving)
  - If the observed frequencies differ significantly from the expected frequencies, the population is evolving

D4.1.15—Artificial selection by deliberate choice of traits

Artificial selection is carried out in crop plants and domesticated animals by choosing individuals for breeding that have desirable traits. Unintended consequences of human actions, such as the evolution of resistance in bacteria when an antibiotic is used, are due to natural rather than artificial selection.

- **Artificial selection** is selection of phenotypic traits that serve human needs & wants
  - Humans select for better **crop plants** by propagating plants with high seed or oil production
  - Humans **domesticate animals** by breeding individuals with desirable traits (like high milk production in cows or certain aesthetic features in dogs)
- Artificial selection is used as evidence for evolution because it can show evolutionary change much faster than what is observed in nature (which normally takes many years)
- Unintended consequences of human actions, such as the evolution of resistance in bacteria when an antibiotic is used, are due to natural rather than artificial selection
  - The antibiotic, while man-made, is a selection pressure that favors resistant bacteria (but resistance is not a desirable trait to artificially select for because it negatively affects humans)

Linking questions

• How do intraspecific interactions differ from interspecific interactions?

• What mechanisms minimize competition?

Review questions

SL and HL

- Define natural selection. [1]
- Explain how the conditions necessary to bringing about natural selection are achieved. [3]
- Outline how intraspecific competition and cooperation contributes to evolutionary change through natural selection. [3]
- Outline the significance of John Endler’s experiments in understanding natural selection. [3]
- Explain how the phenotypes within a population can change with natural selection. [3]
- Distinguish between the two types of selection pressures that promote natural selection. [4]
- Explain how the concept of "survival of the fittest" can be misleading when applied to natural selection. [5]
- Discuss how and why sexual selection may counterintuitively select for traits that do not increase an individual’s chance of survival. [6]
- Discuss the importance of balancing between reproduction and survivability in improving the adaptability of a species to its environment. [7]

Additional higher level

- Distinguish between allele and genotype frequency. [1]
- Predict a Hardy–Weinberg genotype frequency equation for a gene consisting of three alleles. [1]
- Distinguish between natural and artificial selection. [1]
- Explain why changes to the gene pool of a bacterial population with antibiotic resistance are due to natural rather than artificial selection. [2]
- Explain which type of natural selection could result in a high frequency of the heterozygous genotype. [2]
- State **four** assumptions of the Hardy–Weinberg equation. [2]
- Explain the role of the three types of natural selection. [6]

References

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