C4.1 Populations and communities

Interaction and interdependence—Ecosystems

Standard level and higher level: 5 hours

Guiding questions

• How do interactions between organisms regulate sizes of populations in a community?

• What interactions within a community make its populations interdependent?

SL and HL

C4.1.1—Populations as interacting groups of organisms of the same species living in an area
Students should understand that members of a population normally breed and that reproductive isolation is used to distinguish one population of a species from another.
Populations are interacting groups of organisms of the same species living in a given area. Members of a population normally interbreed with each other, and reproductive isolation is used to distinguish one population of a species from another (follows the biological species concept).

C4.1.2—Estimation of population size by random sampling
Students should understand reasons for estimating population size, rather than counting every individual, and the need for randomness in sampling procedures.
Counting all individuals in a population is impractical, so estimates of population size must be made through sampling, which is of two types: • **Random sampling** is the process by which every individual in a population has an equal and independent chance of being chosen in the sample that, in this context, is used to estimate population size. This is important to reduce bias, but it inevitably leads to sampling error. • **Systematic sampling** is the process by which individuals are chosen based on a fixed interval; in a population of size *N*, every k^{th} individual is chosen.

NOS: Students should be aware that random sampling, instead of measuring an entire population, inevitably results in sampling error. In this case the difference between the estimate of population size and the true size of the whole population is the sampling error.
Random sampling does not guarantee that the sample is representative of the entire population, it just ensures that unconscious bias does not affect the results. Therefore, the **sampling error** is the difference between the estimate of the population size and the true size of the whole population.

C4.1.3—Random quadrat sampling to estimate population size for sessile organisms

Both sessile animals and plants, where the numbers of individuals can be counted, are suitable. **Application of skills**: Students should understand what is indicated by the standard deviation of a mean. Students do not need to memorize the formula used to calculate this. In this example, the standard deviation of the mean number of individuals per quadrat could be determined using a calculator to give a measure of the variation and how evenly the population is spread.

Sessile organisms do not locomote; they remain in the same location for most/all of their lives (i.e. plants and corals). **Quadrats** are squares of equal size made out of metal, wood, or plastic that are distributed randomly in a particular location to estimate the abundance or distribution of a species. **Random quadrat sampling** involves distributing quadrats randomly in a given area and counting the number of individuals belonging to one species in all quadrats to estimate its population size.

Standard deviation is a measure of the amount of variation of the values of a variable about its mean; how close or far away the data are to the mean number of the species in any given quadrat. Assuming a large enough sample:

- High standard deviation indicates that there is a lot of variation between quadrats; the species' distribution is patchy and uneven, so the population estimate might not be very accurate.
- Low standard deviation indicates that there is little variation between quadrats; the species is distributed evenly within the area of study so the population estimate is more accurate than that with a high standard deviation.

C4.1.4—Capture–mark–release–recapture and the Lincoln index to estimate population size for motile organisms

Application of skills: Students should use the Lincoln index to estimate population size. Population size estimate = $M \times \frac{N}{R}$, where M is the number of individuals caught and marked initially, N is the total number of individuals recaptured and R is the number of marked individuals recaptured. Students should understand the assumptions made when using this method.

Mobile organisms can locomote from one location to another, and their populations can be estimated through the **capture–mark–release–recapture** method and **Lincoln index**:

- Random samples of the population are captured and these individuals are counted, marked, and then released to mingle with the general population
- The population is resampled after enough time has passed to allow complete remixing of the marked individuals (depends on species' habitat and mobility), and then this equation is used:

$$\text{Population size} = M \times \frac{N}{R} = \frac{n_i \times n_r}{m_r}$$

  - M (n_i) is the number of individuals caught and marked initially
  - N (n_r) is the total number of individuals recaptured
  - R (m_r) is the number of marked individuals recaptured
- Assumptions involved:
  - The **population** is **closed** such that there is no immigration or emigration, which is very rare.
  - All individuals have an equal chance of being caught, which is untrue. Captured individuals that are released may avoid the traps used to capture them if they cause distress. They may also be inclined to fall into the traps if favorable bait is used.
  - Marked individuals are not more or less attractive to predators.
  - All individuals are equally as capable of being caught, which is untrue (individuals at different life stages, seasons, or time of day may be more or less likely to be caught).
  - Capturing does not alter the behavioral pattern of the individual (this may or may not occur).
  - Marked individuals will be randomly distributed after release (this may or may not occur).

C4.1.5—Carrying capacity and competition for limited resources

A simple definition of carrying capacity is sufficient, with some examples of resources that may limit carrying capacity.

Given unlimited resources, populations will grow exponentially. In reality, Earth has finite resources which, eventually, will become scarce enough that individuals within a population have to compete for them (like light, water, and soil nutrients for plants and water, mates, and food for animals).

The **carrying capacity (*K*)** is the maximum population size that a particular environment can support.

C4.1.6—Negative feedback control of population size by density-dependent factors

Numbers of individuals in a population may fluctuate due to density-independent factors, but density-dependent factors tend to push the population back towards the carrying capacity. In addition to competition for limited resources, include the increased risk of predation and the transfer of pathogens or pests in dense populations.

Population growth can be regulated through:

- **Density-dependent factors**: the magnitude of their effects depends on the size of the population at a particular time. They are biotic in nature.
- **Dependent-independent factors**: the magnitude of their effects does **not** depend on the size of the population at a particular time. They are abiotic in nature.

Most density-dependent factors act to **stabilize** a population through negative feedback mechanisms to prevent overpopulation. These include:

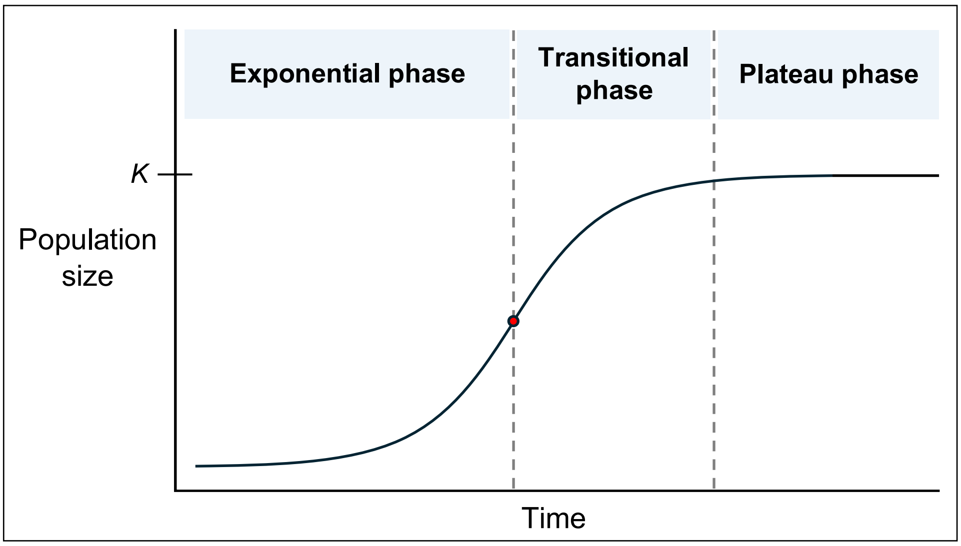
- **Intraspecific competition**: the most significant density-dependent factor that reduces population size. Phenotypic variation among individuals within a population means that some individuals will be better adapted to their environment than others, leading to competition between members of the same population. This may not affect populations well below their carrying capacity, but as the population size increases, intraspecific competition intensifies, which slows down the population's growth.
- **Disease**: big populations tend to be more dense than smaller ones, which increases transmission rates of pathogens or pests, raising mortality.
- **Predation**: big prey populations serve as abundant resources for predators.

Density-dependent factors can operate as positive feedback mechanisms that act to **destabilize** a population, causing it to either grow too fast or shrink too fast. For example:

- Cooperation between members of a large population helps to protect them from predators, which decreases mortality and causes the population to grow.
- In small populations, individuals are more likely to be genetically close (relatives) compared to larger ones. This increases the chance of inbreeding, which reduces genetic diversity and makes the population more vulnerable to further shrinkage.

C4.1.7—Population growth curves

Students should study at least one case study in an ecosystem. Students should understand reasons for exponential growth in the initial phases. A lag phase is not expected as a part of sigmoid population growth.
Application of skills: Students should test the growth of a population against the model of exponential growth using a graph with a logarithmic scale for size of population on the vertical axis and a non-logarithmic scale for time on the horizontal axis.



The **logistic (sigmoidal, S-shaped) model of population growth** is one method of modelling population growth and includes the following phases:

1. **Exponential phase**: the population size increases exponentially because of abundant resources and little to no density-dependent factors or abiotic factors limiting growth.
2. **Transitional phase**: at exactly the middle of the curve (red dot), density-dependent factors begin regulating growth and slowing it down (no longer exponential).
3. **Plateau phase**: birth rate and death rate (mortality) equilibrate; net growth is zero and the population size stabilizes at the carrying capacity, *K*. The population may overshoot or undershoot, oscillating above and under *K* due to random chance or density-dependent and -independent factors.

For example, yeast grown for bread and beverages exhibits an S-shaped curve when grown in a test tube. The harbor seal also exhibits S-shaped growth, but its population fluctuates more than yeast's at the plateau phase due to the influence of more ecological factors.

NOS: The curve represents an idealized graphical model. Students should recognize that models are often simplifications of complex systems.

The logistic model is an idealized graphical model with many underlying assumptions (i.e. it assumes that the density of the population is the only limiting factor). Models are often simplifications of complex systems, but they are useful for conceptual and theoretical understanding of biological phenomena.

C4.1.8—Modelling of the sigmoid population growth curve

Application of skills: Students should collect data regarding population growth. Yeast and duckweed are recommended but other organisms that proliferate under experimental conditions could be used.

A good estimate of population size for yeast is turbidity, and count for duckweed.

C4.1.9—Competition versus cooperation in intraspecific relationships
Include reasons for intraspecific competition within a population. Also include a range of real examples of competition and cooperation.

Intraspecific relationships are the interactions between individuals within a population, including:

- **Intraspecific cooperation** occurs when an individual of a species will help another individual from the same species to improve the chances of survival for both the individuals and the entire group. Examples include parental cooperation and hunting.
- **Intraspecific competition** occurs when members of the same species compete for the same resources, including sunlight, food, mates, or territory.

C4.1.10—A community as all of the interacting organisms in an ecosystem
Communities comprise all the populations in an area including plants, animals, fungi and bacteria.

A **community** is a group or association of all the populations of different species living and interacting with each other in a given geographic location.

C4.1.11—Herbivory, predation, interspecific competition, mutualism, parasitism and pathogenicity as categories of interspecific relationship within communities
Include each type of ecological interaction using at least one example.

Interspecific relationships are the interactions between populations, and are of many types:

- **Herbivory**: consumption of plant material by animals (i.e. giraffes eat acacia leaves).
- **Predation**: a predator species attacks, kills, and eats another prey species (i.e. lynx eat snowshoe hares).
- **Interspecific competition**: two species compete for the same limited resource (i.e. oak tree and balsam fir tree compete for soil minerals and light).
- **Mutualism**: mutually beneficial interactions between members of the same or different species. **Symbiosis** refers to a close and prolonged association between two organisms of different species, which may be beneficial to only one or both species. Mutualistic interactions are not always symbiotic, and symbiotic relationships are not always mutualistic. An example of a mutualistic interaction is between fungi and plants.
- **Parasitism**: a symbiotic relationship in which one species benefits at the expense of another (i.e. parasites of the genus *Plasmodium* cause malaria in humans).
- **Pathogenicity**: the ability of one species to cause disease in another species, i.e. *E. coli* causes disease in humans.

C4.1.12—Mutualism as an interspecific relationship that benefits both species

Include these examples: root nodules in Fabaceae (legume family), mycorrhizae in Orchidaceae (orchid family) and zooxanthellae in hard corals. In each case include the benefits to both organisms.

Note: When students are referring to organisms in an examination, either the common name or the scientific name is acceptable.

1. Root nodules in Fabaceae:
   - *Rhizobium* bacteria live in root nodules of plants in the legume family
   - Bacteria perform **nitrogen fixation**; conversion inert nitrogen (N_2) into ammonia (NH_3) that can be used by plants as fertilizer
   - In exchange, plants provide carbohydrates and a favorable environment for bacteria
2. Mycorrhizae in Orchidaceae:
   - **Mycorrhizae** are symbiotic relationships between fungi and plants
   - Orchid seeds do not have sufficient nutritional reserves to germinate on their own
   - Fungi obtain nutrients from the environment and pass it on to the orchid seed
   - When the orchid plant dies, the fungi benefit by decomposing it
3. Zooxanthellae in hard corals:
   - **Zooxanthellae** are photosynthetic algae that live in the tentacles of **coral polyps**
   - Zooxanthellae provide carbon-based energy for coral polyps
   - Coral polyps (which make up coral reefs), in exchange, provide algae with the minerals and CO_2 they need to photosynthesize, in addition to providing a safe environment for their growth

C4.1.13—Resource competition between endemic and invasive species

Choose one local example to illustrate competitive advantage over endemic species in resource acquisition as the basis for an introduced species becoming invasive.

Endemic species are exclusively found in a specific geographic location/range; they are native to that area and do not exist anywhere else in the world. **Invasive species** are non-native organisms introduced to a new geographic location that begin to spread rapidly and cause harm to the new environment.

Invasive species often outcompete endemic species in resource competition since the density-dependent factors found in their original locations, like predators, do not exist to regulate their populations in new environments.

C4.1.14—Tests for interspecific competition

Interspecific competition is indicated but not proven if one species is more successful in the absence of another. Students should appreciate the range of possible approaches to research: laboratory experiments, field observations by random sampling and field manipulation by removal of one species.

It is difficult to 'prove' that interspecific competition is limiting the populations of two species, since many ecological factors can influence this, but there are tests that indicate whether or not interspecific competition may be playing a role, including:

- **Laboratory experiments**: displacing organisms to controlled laboratory environments helps to reduce the effects of confounding variables and isolates interspecific competition, as much as possible, as the main driver of differences in results.
- **Field observations**: random quadrat sampling and associated chi-squared tests help indicate interspecific competition.
- **Field manipulation**: removing or adding a hypothesized competitor to a specific wild area and observing/measuring its effects on a species allows for more realism than laboratory experiments.

NOS: Students should recognize that hypotheses can be tested by both experiments and observations and should understand the difference between them.

Experiments can prove causation through manipulating one or more variables whilst keeping others controlled to isolate the cause and effect. **Observations** can elucidate patterns or correlations but do not prove causations as they simply involve recording natural phenomena as they occur. Both are useful for testing hypotheses.

C4.1.15—Use of the chi-squared test for association between two species

Application of skills: Students should be able to apply chi-squared tests on the presence/absence of two species in several sampling sites, exploring the differences or similarities in distribution. This may provide evidence for interspecific competition.

The **chi-squared test of association** is a statistical test carried out to determine whether two species tend to occur more or less frequently together more or less often than they would be by random chance. This can help indicate whether the species are in competition/mutualism/parasitism with each other or not.

1. Random quadrat sampling in which the presence or absence of either species is recorded
2. Creation of contingency tables of observed and expected frequencies
3. Calculation of chi-squared (χ^2) value,

$$\chi^2 = \sum \frac{(O - E)^2}{E}$$

4. Determination of the **degree of freedom (df)** and identification of the corresponding **critical value**:

$df = 2$ (since species can either be absent or present; 2 outcomes) $- 1 = 1$

Critical value with df 1 and 95% certainty = 3.841

5. Compare the chi-squared value to the critical value:
   - If χ^2 > critical value, the null hypothesis is rejected. There is strong evidence for a specific interaction (competition/mutualism/parasitism) between the species.
   - If χ^2 < critical value, the null hypothesis fails to be rejected. The species are not interacting in any specific way, and any interaction suggestive of a specific mechanism is purely due to random chance.

C4.1.16—Predator–prey relationships as an example of density-dependent control of animal populations
Include a real case study.

Predator–prey relationships are an example of density-dependent control of animal populations. In simple models, predator and prey cycles have 2 main characteristics:

- **Time-lagged**: when prey populations increase, there is a delayed rise in predator populations, due to the time it takes for predators to reproduce and respond to the abundance of prey. This also holds true when prey populations decrease.
- **Synchronous**: the population sizes of predators and prey fluctuate in a coordinated, cyclical manner with time. Changes in one population cause subsequent changes in the other.

A well-documented case study of this model is the Canadian lynx (predator) and snowshoe hare (prey). However, for most real-world scenarios, this model is oversimplified since many other ecological factors influence the predator and prey populations.

C4.1.17—Top-down and bottom-up control of populations in communities
Students should understand that both of these types of control are possible, but one or the other is likely to be dominant in a community.

Populations within communities can be regulated/controlled through two main mechanisms:

- **Top-down control**: a reduction in a species' population due to higher trophic levels feeding on it (i.e. predation or herbivory). This is more likely to be dominant in terrestrial ecosystems.
- **Bottom-up control**: a reduction in a species' population due to limited resources (i.e. lack of minerals/nutrients for plants and low prey populations for predators). This is more likely to be dominant in marine ecosystems.

C4.1.18—Allelopathy and secretion of antibiotics
These two processes are similar in that a chemical substance is released into the environment to deter potential competitors. Include one specific example of each—where possible, choose a local example.

Allelopathy is the direct or indirect effects of chemicals produced by an organism on the germination, growth, survival, and reproduction of other organisms.

- In plants, **primary metabolites** are used for growth, survival, and reproduction, whereas **secondary metabolites** are used for ecological interactions, including harmful ones like competition. For example, **milkweeds** (genus, Asclepias) secrete a white sap containing **cardenolides**, which is toxic to many species including humans.
- In fungi, allelopathy manifests through the production of antibiotics that kill competing bacteria. For example, *Penicillium rubens* produces **penicillin**, which disturbs metabolic processes in bacteria and inhibits their growth.

Note: There is no additional higher level content in C4.1.

Linking questions

• What are the benefits of models in studying biology?

• What factors can limit capacity in biological systems?

Review questions

- Define a population. [1]
- Define random sampling. [1]
- State **one** feature of a community. [1]
- Compare and contrast intraspecific and interspecific competition. [2]
- Explain how allelopathy depends on interactions between species. [4]
- Outline the advantages and disadvantages of models in studying populations. [4]
- Herbivorous animals are more likely to have a varied diet compared to herbivorous insects. Compare how this might affect the coevolution of each herbivore with plants. [5]
- Describe, using examples, the different categories of interspecific relationships within communities. [7]
- Discuss the role of intraspecific cooperation and competition in the evolution of a species. [7]
- Discuss the role of negative feedback in regulating populations. [7]
- Describe the logistic model of population growth, outlining its benefits and limitations. [8]
- Describe how interactions between organisms regulate their populations. [8]
- Describe how you would determine whether two plant species are competing with each other. [8]

References

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