IB DP BIOLOGY

Theme C: Interaction and Interdependence

C4.1 Populations and Communities

Revision Notes · Standard and Higher Level

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Original notes prepared for the IB Diploma Programme Biology course (2025 syllabus)

What the syllabus requires

C4.1 examines how organisms of the same and different species live together, how population sizes are measured and change over time, and how interactions between species shape a community. Use this checklist before the exam.

Understanding	You should be able to...
Populations and communities	Define population and community, and place them within the levels of ecological organisation.
Estimating population size	Apply random quadrat sampling to plants and sessile organisms, and capture-mark-release-recapture (Lincoln index) to mobile animals.
Carrying capacity	Interpret the sigmoid population growth curve and explain what sets the carrying capacity.
Limiting factors	Distinguish density-dependent from density-independent factors and explain how they return a population toward K.
Interactions between species	Classify herbivory, predation, competition, mutualism, parasitism and pathogenicity, with examples.
Predator-prey cycles	Describe and interpret coupled predator-prey population oscillations.
Top-down / bottom-up (HL)	Explain top-down and bottom-up control and the role of keystone species; use indices to compare communities.

> **Exam note:** The core of C4.1 is common to SL and HL. Points flagged **(HL)** in these notes are assessed only at Higher Level, often in data-analysis questions that combine sampling, statistics and community ecology.

1. Levels of ecological organisation

Ecology is studied at a hierarchy of scales. Each level contains the ones before it and adds new interactions.

Level	Definition	Example
Population	All the individuals of the **same species** living in the same area at the same time, able to interbreed.	All the grey squirrels in one woodland.
Community	All the populations of **different species** living and interacting in the same area.	The squirrels, oak trees, fungi, birds and insects of that woodland.
Ecosystem	A community together with the **abiotic** (non-living) environment, and the interactions between them.	The woodland community plus its soil, water, air and light.
Biosphere	The sum of all ecosystems on Earth; the zone of the planet occupied by living organisms.	The whole living surface layer of the Earth.

A **species** is a group of organisms that can interbreed to produce fertile offspring. A **habitat** is the specific place where an organism lives. Note the key jump: a population is one species, a community is many species, and an ecosystem adds the physical environment.

> **Definition trap:** Examiners frequently deduct marks for loose definitions. A population is one species in one area *at one time*; a community is the living component only, so it must not include abiotic factors such as temperature or soil.

2. Estimating population size

It is rarely possible to count every individual, so ecologists estimate population size from a sample. The method chosen depends on whether the organism stays still.

2.1 Random quadrat sampling (plants and sessile organisms)

A quadrat is a square frame of known area (commonly 0.25 m^2, i.e. 0.5 m × 0.5 m) placed on the ground to sample what lies within it. It suits organisms that do not move: plants, algae, barnacles, limpets and mussels.

Method:

- Lay two tape measures at right angles along the edges of the study area to form a coordinate grid.
- Use a random-number generator to produce pairs of coordinates, so that every point has an equal chance of being sampled and personal bias is removed.
- Place the quadrat at each random coordinate and record what is inside.
- Repeat for many quadrats (the more samples, the more reliable the mean), then scale up to the whole area.

Two quantities can be recorded from each quadrat:

Measure	How it is found	Best for
Population density	Count the number of individuals in the quadrat; density = mean count per quadrat → individuals per m^2.	Plants that are easily counted as separate individuals (e.g. daisies).
Percentage cover	Estimate the % of the quadrat area covered by the species, often using a gridded quadrat of 100 small squares.	Species hard to count as individuals (e.g. grasses, mosses, lichens).

To estimate total population size: mean number per quadrat × (total area ÷ area of one quadrat). Percentage cover does not give a total count but allows the abundance of a species to be compared between sites or over time.

> **Why random?** Random sampling avoids the bias of choosing 'interesting' spots and lets the sample represent the whole area. If you are instead studying how a species changes across a gradient (e.g. up a shore), use a *belt transect* with quadrats placed systematically along a line, not random placement.

2.2 Capture-mark-release-recapture (mobile animals)

Animals that move cannot be sampled with a quadrat, so a mark-recapture method is used to estimate population size *N* with the **Lincoln index**.

Method:

- Capture a first sample, count them (M), mark each one harmlessly, and release them.
- Allow time for the marked individuals to mix randomly back into the population.
- Capture a second sample; count the total caught (n) and how many of them carry a mark (m).
- Estimate the population from the Lincoln index below.

$$N = (M \times n) \div m$$

where M = number marked and released, n = total in second sample, m = marked individuals recaptured, and N = estimated population size. The logic is that the proportion of marked animals in the second sample equals the proportion of marked animals in the whole population.

Assumptions (all must hold for the estimate to be valid):

- Marked individuals mix evenly and randomly with the rest of the population.
- The mark is not lost, and does not harm the animal or make it more visible to predators.
- No significant births, deaths, immigration or emigration between the two samples (population is effectively closed).
- Marked animals have the same chance of being recaptured as unmarked ones (no 'trap-shyness' or 'trap-happiness').

> **Common error:** If any assumption is broken the estimate is skewed in a predictable direction. For example, if marking makes prey easier to catch, m rises and the calculated N is too small.

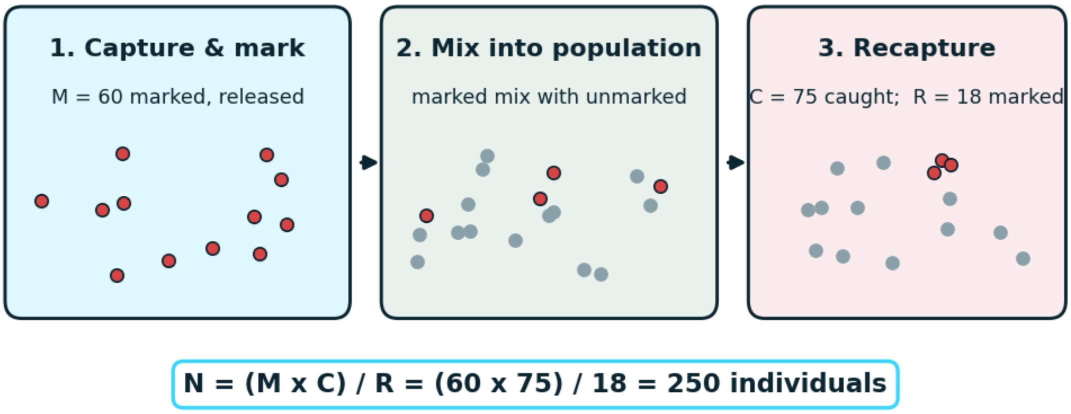

Figure 3. Capture-mark-release-recapture. The Lincoln index gives N = (M × C) / R = (60 × 75) / 18 = 250 individuals (marked animals shown in red).

3. Population growth and the sigmoid curve

When a small population colonises a new area with abundant resources, its size over time typically follows an **S-shaped (sigmoid) curve**. It has three phases.

Phase	What happens	Why
Exponential (log) phase	After a brief lag, numbers rise faster and faster; the curve steepens.	Resources (food, space) are plentiful and unlimited; natality far exceeds mortality; few limiting factors act.
Transitional phase	Growth slows; the curve begins to level off.	Resources start to run short and limiting factors increasingly act; natality falls and/or mortality rises.
Plateau (stationary) phase	Population size fluctuates around a stable maximum.	Natality ≈ mortality; the population has reached the carrying capacity of the environment.

The **lag phase** at the very start is the slow initial period when numbers are low and individuals are acclimatising or few reproducers are present. It is sometimes shown as a short flat region before the exponential rise.

Carrying capacity (K)

The **carrying capacity** is the maximum population size that an environment can support indefinitely, given the available resources. It corresponds to the plateau of the sigmoid curve. K is not fixed forever: if resources increase (e.g. a good season) K rises, and if they fall K drops.

Why exponential growth cannot continue

During true exponential growth the population would double in fixed time intervals and rise without limit. This is impossible in nature because the environment holds only finite resources. As density rises, individuals compete for food, water, space and mates; wastes accumulate; and disease and predation intensify. These limiting factors reduce the net growth rate to zero at K.

> **Exam phrasing:** Say the growth rate (not the population) falls to zero at the plateau. At K the population is still large and reproducing - births and deaths are simply balanced.

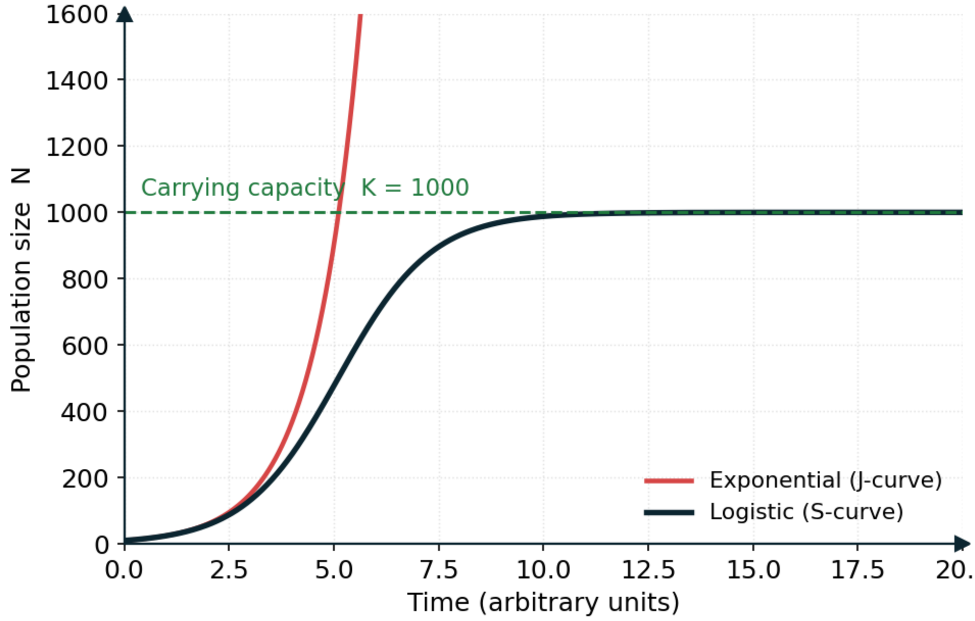

Figure 1. Exponential (J-curve) growth is unbounded, but logistic (S-curve) growth levels off at the carrying capacity K. Computed from $N(t) = K/(1 + ((K-N_0)/N_0)\, e^{-rt})$ with K = 1000, r = 0.9, N_0 = 10; N → K as t increases.

4. Factors that limit population growth

Limiting factors are the environmental factors that slow, stop or reverse population growth. They fall into two groups according to whether their effect depends on how crowded the population is.

	Density-dependent factors	Density-independent factors
Depend on population density?	Yes - their effect strengthens as the population becomes more crowded.	No - their effect is the same whatever the density.
Nature	Mostly **biotic**: competition for food/space, predation, disease and parasitism, accumulation of wastes.	Mostly **abiotic**: extreme temperature, drought, flood, fire, storms and other natural disasters.
Effect on population	Regulate the population around K by negative feedback: above K they lower growth, below K they relax.	Can cause sudden large changes regardless of size; do not track K and cannot regulate to a set point.

How density-dependent factors return a population toward K

Density-dependent factors act as a negative feedback loop:

- If the population rises above K, competition intensifies, food per individual falls, and disease and predation increase → mortality rises and/or natality falls → the population falls back toward K.
- If the population drops below K, resources become plentiful again, competition eases → natality rises and mortality falls → the population grows back toward K.

This self-correcting behaviour is why populations tend to fluctuate around, rather than settle exactly on, the carrying capacity.

> **Contrast to remember:** A harsh frost that kills the same proportion of insects whether there are 100 or 10 000 of them is density-independent. Starvation that bites harder the more crowded the population is is density-dependent.

5. Interactions between species

Within a community, populations of different species interact. The interactions are classified by their effect on each partner: benefit (+), harm (–) or no significant effect (0). **Symbiosis** is a general term for a close, long-term association between two species living together; mutualism, parasitism and commensalism are all forms of symbiosis.

Interaction	Effect	Description	Example
Competition	– / –	Both species need the same limited resource; each is worse off.	Two plant species competing for light and soil nitrate.
Predation	+ / –	One organism (predator) kills and eats another (prey).	Lynx hunting snowshoe hare.
Herbivory	+ / –	An animal eats part of a plant; the plant is damaged, not always killed.	Deer grazing on grasses and shrubs.
Mutualism	+ / +	Both species benefit from the association.	Root nodule bacteria (Rhizobium) and legumes; mycorrhizae and tree roots.
Parasitism	+ / –	A parasite lives in or on a host, gaining nutrients and harming it.	Tapeworm in a mammal gut; ticks on a deer.
Commensalism	+ / 0	One species benefits; the other is essentially unaffected.	Epiphytic orchids growing on a tree branch for support.
Pathogenicity	+ / –	A pathogen (microbe) infects a host and causes disease.	Bacterium causing infection in an animal host.

Intraspecific vs interspecific competition

- **Intraspecific competition** is between members of the *same* species. It is usually the more intense, because individuals need identical resources; it is the main density-dependent brake that produces the carrying capacity.
- **Interspecific competition** is between members of *different* species with overlapping requirements. It can reduce the population size of both, or exclude one species from part of the habitat.

Competitive exclusion and resource partitioning

The **competitive exclusion principle** states that two species competing for exactly the same limiting resource cannot coexist indefinitely: the better competitor eventually excludes the other from that habitat. Species that do coexist usually avoid this by **resource partitioning** - using the shared resource in slightly different ways (for example feeding at different times, in different parts of a tree, or on different food sizes). This reduces the overlap in their requirements so that interspecific competition is weakened and both populations persist.

> **Note:** The same '+ / –' sign pattern covers predation, herbivory, parasitism and pathogenicity. Distinguish them by *what* is consumed and *how*: predators kill and eat whole prey, herbivores eat plant tissue, parasites live on/in a host over time, and pathogens cause disease.

6. Predator-prey population cycles

Where a predator depends heavily on a single prey species, the two population sizes often oscillate in linked cycles - the classic example being the Canada lynx and the snowshoe hare. The two curves rise and fall with the **predator peak lagging behind the prey peak**.

Why the cycles oscillate out of phase:

- Plentiful prey provides abundant food, so the predator population grows (more food → higher predator natality, lower mortality).
- The now-large predator population eats prey faster than the prey can reproduce, so the prey population falls.
- With prey scarce, predators starve and their population falls shortly after the prey decline.
- Relieved of heavy predation, the prey population recovers - and the cycle repeats.

Because each population responds to a *change* in the other, the predator numbers peak a little after the prey numbers: the curves are shifted (out of phase) rather than moving together. This is a density-dependent, negative-feedback interaction. Real cycles are also influenced by food supply for the prey, so the relationship is rarely as clean as the textbook diagram.

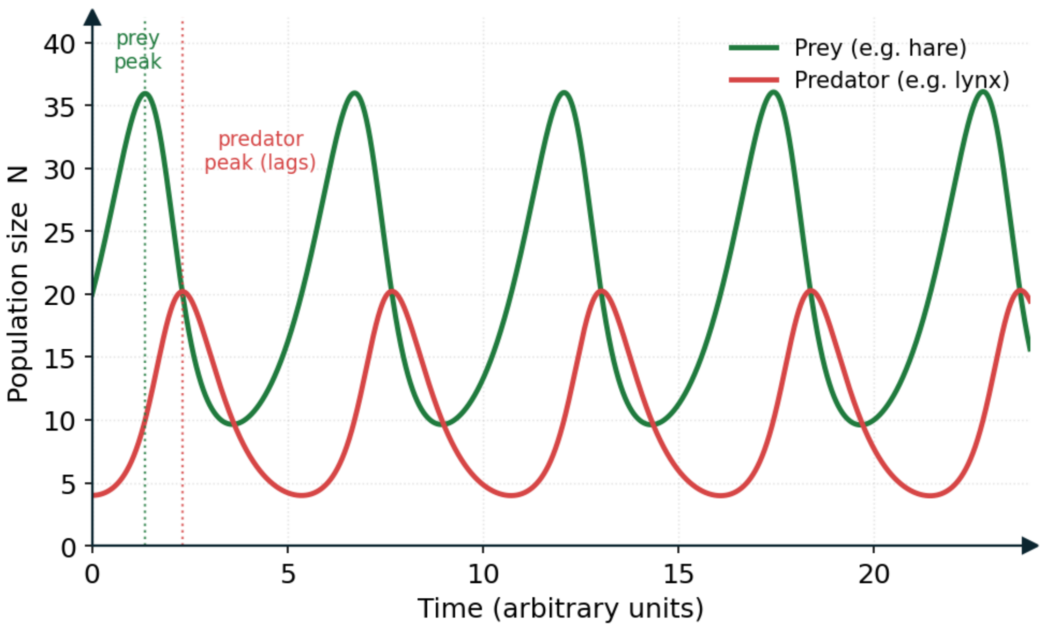

Figure 2. Coupled predator-prey cycles (a Lotka-Volterra model). The predator peak comes after the prey peak, so the two populations oscillate out of phase.

> **Interpretation tip:** In an exam graph, identify which curve peaks first: the prey peak always comes *before* the predator peak. Do not claim the predator alone controls the prey - prey food supply matters too.

7. Top-down and bottom-up control; keystone species

Communities can be regulated from either end of the food chain.

- **Top-down control:** population sizes are set mainly by consumers/predators higher in the food chain. Removing a top predator lets herbivores increase and overgraze the plants below.
- **Bottom-up control:** population sizes are set mainly by the supply of resources at the base (nutrients, light, primary producers). More nutrients → more producers → more consumers up the chain.

Keystone species

A **keystone species** has an effect on community structure far greater than its abundance would suggest. Removing it causes disproportionate change and can collapse the community's structure. A classic case is a predatory sea star whose removal lets mussels dominate a rocky shore, crowding out other species and reducing diversity - an example of top-down control by a keystone predator.

8. (HL) Comparing communities and limiting resources

At Higher Level you are expected to use quantitative tools to compare communities and to reason about limiting resources.

8.1 Using statistics and indices to compare communities (HL)

- **Statistical comparison of means:** when comparing the mean abundance of a species at two sites, a *t*-test assesses whether the difference is statistically significant or could be due to chance. Large, overlapping error bars suggest no significant difference.
- **Diversity indices:** a diversity index (such as Simpson's reciprocal index) combines the number of species (*richness*) and how evenly individuals are shared among them (*evenness*) into a single value. A higher index means a more diverse - and often more stable - community.
- **Correlation:** the strength of a relationship between an abiotic factor and a species abundance can be measured with a correlation coefficient; correlation alone does not prove causation.

8.2 Further sampling considerations (HL)

- **Sample size:** too few quadrats or too small a marked sample gives a wide, unreliable estimate. Increasing replication narrows the confidence in the mean.
- **Quadrat size and placement:** the quadrat must be large enough to capture the pattern of the species but small enough to count; placement must stay genuinely random to avoid bias.
- **Choosing the method:** match the technique to the organism - quadrats for sessile species, mark-recapture for mobile animals, transects for gradients.

8.3 The effect of a limiting resource (HL)

A **limiting resource** is the resource in shortest supply relative to demand; it is the one that actually caps the population, even when others are plentiful. As a population grows, demand for the limiting resource rises until it constrains further growth, setting the carrying capacity. Increasing the supply of the limiting resource (e.g. adding nitrate to a nutrient-poor lake) raises K and allows the population to grow further - until a different resource becomes limiting in turn.

HL exam skill: When a graph shows a population plateau, be ready to name a plausible limiting resource and explain, using density-dependent competition, how it holds the population at K.

9. Worked examples and skills

Worked example 1 - Lincoln index

Ecologists studying woodlice capture and mark **60** individuals and release them. A few days later they capture a second sample of **75** woodlice, of which **18** are marked. Estimate the population size.

$M = 60$, $n = 75$, $m = 18$.

$N = (M \times n) \div m = (60 \times 75) \div 18 = 4500 \div 18 =$ **250 woodlice**.

Check the assumptions: marks retained, marked animals mixed back in, and no major birth/death/migration between samples.

Worked example 2 - quadrat density and percentage cover

A field of area **800 m^2** is sampled with a 0.25 m^2 quadrat placed at 10 random positions. The dandelion counts are: 3, 5, 2, 4, 6, 3, 5, 4, 2, 6. Estimate (a) the mean density and (b) the total dandelion population.

(a) Total counted = 40 over 10 quadrats → mean = 4.0 per quadrat. Each quadrat is 0.25 m^2, so density = 4.0 ÷ 0.25 = **16 dandelions per m^2**.

(b) Total population = density × area = 16 × 800 = **12 800 dandelions** (equivalently mean 4.0 × 800/0.25 = 4.0 × 3200).

If instead the quadrat showed the species covered on average 35 of the 100 grid squares, the percentage cover would be **35%** - useful for grasses that cannot be counted individually.

Worked example 3 - classify an interaction

Oxpecker birds ride on buffalo and eat ticks and parasites from the buffalo's skin. Classify the two relationships involved.

Oxpecker and tick: the bird gains food and the tick is eaten → **predation (+/–)**.

Oxpecker and buffalo: the bird gains food and the buffalo loses parasites and is cleaned → both benefit → **mutualism (+/+)**, a form of symbiosis.

Worked example 4 - interpret a growth curve

A yeast culture is counted each hour. Numbers stay low for 2 h, rise steeply from 2-8 h, then level off near 9×10^6 cells cm^{-3} after 10 h. Label the phases and state the carrying capacity.

0-2 h: **lag phase** (cells acclimatising, few reproducers). 2-8 h: **exponential (log) phase** (abundant glucose, minimal limiting factors). 8-10 h: **transitional** as growth slows. After 10 h: **plateau/stationary phase**.

Carrying capacity K ≈ **9×10^6 cells cm^{-3}**, set as glucose runs low and ethanol waste accumulates (density-dependent factors).

Worked example 5 - interpret a predator-prey graph

A graph shows hare numbers peaking at year 3 and lynx numbers peaking at year 4, with both cycling every ~4 years. Explain the one-year offset.

Abundant hares (year 3) provide food, so lynx numbers rise and peak one year later (year 4). The large lynx population then over-hunts the hares, so hare numbers fall; lynx starve and decline shortly after.

The predator peak **lags** the prey peak because the lynx population responds to the *change* in hare abundance, keeping the two curves out of phase.

10. Common pitfalls

- **Lincoln index assumptions:** forgetting to state that the population is closed and marks are not lost - these are common mark-award points.
- **Density-dependent vs independent:** a factor is density-dependent only if its *effect* changes with crowding, not simply because it is biotic. Extreme weather is density-independent even though it can be severe.
- **Carrying capacity:** K is where the *growth rate*, not the population, is zero. The population is large and still reproducing at K.
- Confusing **community** (living only) with **ecosystem** (living plus abiotic).
- Claiming that 'the predator alone controls the prey' without noting that prey food supply and other factors also drive the cycle.
- Reporting a quadrat estimate to more figures than the sampling justifies - estimates are approximate.

11. Quick reference

Term / result	Statement
Population	Individuals of one species, one area, one time, able to interbreed.
Community	All interacting populations of different species in an area (living only).
Lincoln index	$N = (M \times n) \div m$ for mobile animals.

Term / result	Statement
Quadrat density	individuals per m^2 = mean count per quadrat ÷ quadrat area.
Sigmoid phases	lag → exponential (log) → transitional → plateau (stationary).
Carrying capacity (K)	Maximum population an environment can support indefinitely; growth rate = 0 at K.
Density-dependent	Biotic factors (competition, predation, disease) whose effect rises with crowding; regulate to K.
Density-independent	Abiotic factors (climate, disasters) with the same effect at any density; do not regulate to K.
Interaction signs	predation/herbivory/parasitism/pathogen +/–; competition –/–; mutualism +/+; commensalism +/0.
Predator-prey	Coupled cycles; predator peak lags prey peak (out of phase).
Keystone species	Disproportionate effect on community structure relative to its abundance.

12. Practice questions

Attempt these without notes; full worked answers follow.

1. Define *population* and *community*, and explain how they differ from an ecosystem. [3]

2. A student marks 48 snails, releases them, and later recaptures 60 snails of which 16 are marked. Estimate the population and state two assumptions. [4]

3. Explain why a population growing exponentially cannot continue to do so indefinitely. [3]

4. Distinguish between density-dependent and density-independent limiting factors, giving one example of each. [4]

5. A 500 m^2 lawn is sampled with a 0.25 m^2 quadrat; the mean plantain count is 3.0 per quadrat. Estimate the total plantain population. [3]

6. Classify each relationship: (a) tick on a dog, (b) bee and flowering plant, (c) two oak seedlings competing for light. [3]

7. In a predator-prey graph the prey peaks before the predator. Explain why the two curves are out of phase. [3]

8. (HL) Explain how increasing the supply of a limiting resource affects the carrying capacity of a population. [3]

Worked answers

1. A population is all the individuals of one species living in the same area at the same time and able to interbreed; a community is all the populations of different species interacting in that area (living component only). An ecosystem is the community plus the abiotic environment and their interactions - so it adds the non-living factors that a community excludes. [3]

2. $N = (M \times n) \div m = (48 \times 60) \div 16 = 2880 \div 16 =$ **180 snails**. Assumptions (any two): marked snails mix randomly; marks are not lost or harmful; no significant birth/death/migration between samples; marked and unmarked equally likely to be recaptured. [4]

3. Exponential growth needs unlimited resources, but every environment is finite. As density rises, individuals compete for food, space and mates, wastes build up, and disease and predation increase; these density-dependent factors lower natality and raise mortality until the growth rate falls to zero at the carrying capacity. [3]

4. Density-dependent factors have an effect that strengthens as the population becomes more crowded and are mostly biotic - e.g. competition for food (or predation/disease). Density-independent factors have the same effect whatever the density and are mostly abiotic - e.g. a frost, flood or fire. Only density-dependent factors regulate the population around K. [4]

5. Density = 3.0 ÷ 0.25 = 12 plantains per m^2. Total = 12 × 500 = **6000 plantains** (equivalently 3.0 × 500/0.25). [3]

6. (a) Parasitism (+/–) - the tick gains, the dog is harmed. (b) Mutualism (+/+) - the bee gains nectar, the plant is pollinated. (c) Intraspecific competition (–/–) - same species competing for the same resource. [3]

7. When prey are abundant the predators have plentiful food, so predator numbers rise and peak *after* the prey peak. The large predator population then reduces the prey; with prey scarce, predators decline. Because each population responds to the change in the other, the predator curve lags the prey curve, so they are out of phase. [3]

8. (HL) The limiting resource is the one in shortest supply that caps growth. Increasing its supply means the population can grow larger before that resource again becomes limiting, so the carrying capacity rises and the plateau of the growth curve shifts upward - until another resource becomes the new limiting factor. [3]