Lecture 2: Surface Area to Volume (SA/V) Ratio

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This Lecture is Accompanied by the Following Lab

- Lab 1: Surface Area to Volume (SA/V) Ratios in Biology

Content

- Surface Area to Volume Ratio, a universal law in biology.
- Understanding the plant (and algal) body plan.
- The major 'functions' of plants that are affected by SA:V ratio.
- Littler and Litter's (1980) and Littler and Arnold's (1982) functional form model (in seaweeds).
- Extending the functional form model to seagrasses (distribution, ecophysiology, and ecological interactions).

Aims

In this lecture, I will introduce students to the concept of the surface area to volume (SA:V) ratio as a fundamental biological principle that influences the structure and function of all living organisms. You will explore how this ratio affects the body plan and physiological processes of plants and algae,and how it shapes key functions such as nutrient absorption, gas exchange, and growth. We will delve into Littler and Littler's (1980) and Littler and Arnold's (1982) functional form model for seaweeds, which illustrates the ecological relevance of SA:V ratios in marine environments. Additionally, we will extend this model to seagrasses, and focus on their distribution, ecophysiology, and ecological interactions. The overarching goal is to equip you with the ability to connect this universal biological law to plant form and function in a variety of ecosystems.

Learning Outcomes

By the end of this lecture, you will be able to:

1. Define the surface area to volume (SA:V) ratio and explain why it is a universal biological principle that governs the form and function of living organisms.
2. Understand the relationship between the SA:V ratio and plant body plans, with specific reference to how this ratio affects the structure and function of plants and algae.
3. Describe the major physiological functions of plants that are influenced by the SA:V ratio, such as nutrient uptake, gas exchange, and water balance.
4. Explain Littler and Littler's (1980) and Littler and Arnold's (1982) functional form model for seaweeds, identifying how the SA:V ratio plays a role in determining the ecological strategies of marine macroalgae.
5. Extend the functional form model to seagrasses, analysing how their SA:V ratio influences their distribution, physiological adaptations, and ecological interactions in marine ecosystems.
6. Apply the concept of SA:V ratios to broader ecological contexts, demonstrating an understanding of how this principle affects organismal form and function across terrestrial and marine environments.

1 Introduction: Surface Area and Volume Ratio

So let's continue with our lectures today. Now, we're going to talk a bit about surface area and volume ratio. You will have already encountered some of these calculations in your practical, in the very first lab that you had, so much of it should be quite intuitive to you by now. I think Brian would have also spoken a bit about the constraints imposed on animal behaviour, on its physiology, that stem from the relationship between the ratio of an animal's surface area to its volume. The same kind of thing, of course, would happen in plants. It's one of the most fundamental processes that places various different limits on the way in which various physiological rate processes work.

2 Surface Area to Volume Ratio: Definitions and Importance

So, when we talk about the surface area to volume ratio, we talk about the flat external surface—the skin, the total volume of skin around a human body, or the two sides of a leaf, which is typically measured in area, in square centimetres. The ratio of that quantity to the volume of something, which is the internal bulk of an organism—everything below your skin, or your meat, bones, and organs, or within, say, the leaf, where you might have one, two, or three layers of cells. So the ratio of these things—the surface area measured in square centimetres to the volume in cubic centimetres—is what's commonly called the surface area to volume ratio.

Plants in their day-to-day lives require various things that they need to do. They need to capture photons—they need to harvest light, in other words—so leaves provide a convenient two-dimensional flat surface, of which we can calculate the size, which translates directly to one of the units in the quantum measurement of light intensity, so metres squared. So the surface area of a leaf relates directly to the amount of area available for photon capture. It's quite easy to derive the total amount of photons falling onto a leaf surface if you know the total area in square centimetres of that leaf.

Plants must also acquire water and take up nutrients together with that water, and they must distribute all of these materials from the roots via the stems to the leaves. When they photosynthesise, one of the byproducts is oxygen. The oxygen must be released back into the atmosphere, and that's happening via the leaves again. So, the more surface area there is, the greater the area available for oxygen exchange. Similarly, the same holds true for carbon dioxide—the greater the surface area available within the leaf, the greater the amount of area exposed to the atmosphere by which carbon dioxide can be released back, or taken up from the atmosphere, into the leaves. There are various different metabolic wastes that need to be disposed of, which typically happens in the roots and so on.

All of these operations require—or are based upon—various chemical, physical, and biological principles that impose various constraints on the rate at which these processes can operate. All of these functions are also constrained by the various parts of a plant body, the thallus. It helps us to also understand the construction—"construction" in inverted commas, because it hasn't been constructed by a person, it just evolved. So we need to understand the various components that form the structure of a full plant body that permit these various different operations: CO_2 uptake, waste disposal, water uptake, and all of these.

3 Plant Structures and Surface Area to Volume Relationships

When we talk about higher plants, these would typically be the things that we see outside the window. If you walk around in nature, these would be angiosperms and gymnosperms. All of them are comprised of roots, stems, and leaves.

The roots, of course, are the bits below the ground surface, which serves several purposes. From an ecophysiological point of view, the most important surface function is that it interacts with the soil, which is where the water is and where the nutrients are, which are taken up by the roots from the soils and transported up the stems to the leaves. Also, roots fulfil an anchorage purpose as well. You can imagine that things with a high surface area to volume ratio—adventitious roots with lots of fine root hairs—have more surface area in contact with the soil particles themselves. They become very effective at taking up water and nutrients from the soil and bringing it into the plant. So that's a function of a high surface area to volume ratio—the high surface area is associated with direct contact with the soil.

On the other hand, as surface area to volume ratio decreases, the amount of bulk increases. That you typically see under the soil surface as tap roots—deep roots that are quite important for anchoring large plants. They can penetrate quite deep into the soil—maybe towards the water table, far down where it can access water. Anchorage structures, root structures that have a low surface area to volume ratio but more bulk relative to the surface, are very good at anchorage, whereas as soon as roots branch out more, reducing the amount of bulk relative to surface area, you have more contact with the soil, and can access nutrients and water.

The stems, similarly—in very fine ephemeral plants, would have a high surface area to volume ratio. They tend to be flimsy, not very strongly constructed, but as soon as the trees become larger, taller in stature, the surface area to volume ratio of the trunk decreases. There's more volume relative to the external skin, the bark, and therefore it becomes far more strong in terms of its ability to sustain all the bulk above ground. So contrast very large, thick tree trunks to the very thin little stems of ephemeral plants—very different in terms of surface area and volume ratio, and also in terms of the structural strength of these various plant components.

Leaves, of course, are just flat surfaces, very strongly packed with chlorophyll a. Some leaves might become increasingly bulky, with more internal volume relative to the amount of surface area, and so they're able to store more water, becoming more adapted to drier climates. More ephemeral plants —things that have to grow a lot faster, like lettuces for instance—are very flimsy, and as soon as you leave them out in the sun, they wilt very quickly. That's a function of a high surface area to volume ratio. Things like a cactus, for instance, have a huge amount of bulk; you leave it in the sun, and it sits there, fine, for weeks and months. That's because there's very little surface area relative to the amount of bulk through which water loss can take place.

So, it's quite easy to understand how the surface area to volume ratio constraint imposes various different adaptive or evolutionary benefits to plants to survive under certain conditions and environments. It's very easy to see when you walk around in nature, moving from forested areas at high latitudes to the tropics at low latitudes—the plants become very different in appearance and form, going from wet mesic areas to dry environments, to desert kinds of environments. The reason they look different is because there are major changes in the ratio of surface area relative to the volume of these plants.

4 Surface Area to Volume Ratio in Seaweeds (Macroalgae)

Plant structure concepts can also be translated to seaweeds—algae that live in the ocean or in fresh water. They have similar structures, though called something else. In seaweeds, you typically have not roots but a holdfast which is just like a hand—sometimes called a hapteron (plural haptera)— looks like a hand that grabs onto something for anchorage. The only purpose of a hapteron is to anchor a seaweed onto the ground, and larger seaweeds have larger haptera in order to grab onto more surface area and more rock, so that they can anchor better, especially in wavy environments.

There is also a stipe, which is equivalent in terrestrial plants to the stem, but in seaweeds is called the stipe. Then there are the fronds, which are equivalent in function to the leaves in higher plants. We see various surface area to volume ratio variations across seaweed types, as outlined in one of the papers you're meant to read.

Together, the holdfast, the stipes and the fronds are called the thallus (plural thalli).

5 Littler et al.: Functional Form Groups in Macroalgae (Reference to Slide/Paper)

This is the important paper that you need to read. It was published originally in the late 1970s by Mark and Diane Littler, but the one I want you to read for this lecture is on eConver—go and download it. It's called "Primary Productivity of Marine Macroalgae or Marine Macroalgal Functional Form Groups from Southwestern North America." What Mark and Diane Littler did, and Keith Arnold in later collaborations, was to look at functional forms of seaweeds, dividing them into different groups, each characterised by different surface area to volume ratios. The experiments clearly show that as surface area and volume ratio changes, various ecophysiological functions of the algae change.

There were about six groups of functional forms. At one extreme are very thin, sheet-like forms—think of a lettuce, like cos lettuce. In fact, one seaweed they studied is called sea lettuce—Ulva is the common name because it has a similar appearance. As the seaweeds become increasingly complex, like filamentous or coarsely branched groups, the internal bulk increases and the surface area relative to bulk decreases. So, going from sheet-like at the top of the table to crustose at the bottom, you see a decrease in surface area to volume ratio as complexity increases.

We can look at some examples. Sea lettuce (Ulva) looks very similar to lettuce, and Porphyra umbilicalis—Porphyra is the seaweed used to make nori for sushi, commonly seen in Asian foods [note: Porphyra is correct, but in South Africa, it is not native; it's mainly an import] [attention]. Ulva and Porphyra are examples of the thin tubular and sheet-like group—characterised by high surface area to volume ratios. There's much more surface compared to the bulk inside.

If you look at the measurement of photosynthesis—the rate of carbon fixation, so milligrams of carbon per gram dry mass per hour—you'll see that the values for these groups extend to quite high ranges, with high averages around 5 or 6 mg C/g dry mass/hour. For more complex forms—delicately branched, coarsely branched—the average value is lower, and as you move to even more complex functional forms, the photosynthetic efficiency decreases. This is because surface area to volume ratio declines—less surface area is available to capture carbon and exchange with the environment, thus constraining the rate of photosynthesis.

So, as surface area to volume ratio decreases, the ability of the plant to harvest enough carbon for fast growth rates also decreases. In simple seaweeds, plenty of surface area means efficient carbon access for the one or two cell layers, but in complex forms, there's less exchange and more constraints.

6 Broader Consequences and Applications

This constraint acts not only on carbon dioxide uptake and photosynthesis, but also on oxygen release, water and nutrient uptake, metabolic wastes disposal, and so on. The same principle applies to terrestrial plants.

7 Surface Area to Volume Ratio in Seagrasses

Now, let's extend this analysis to seagrasses. Seagrasses are, of course, angiosperms. They are different from true grasses but have evolved from land plants to reoccupy marine spaces. If you dive in seagrass meadows, for instance in Australia where these are abundant, it looks like a lawn of grass underwater. These meadows are often dominated by one or a few seagrass species.

Seagrasses display a spectrum from very simple to very complex. On the left, we have fast-growing halophila (high surface area to volume ratio); on the right, we have larger, more complex forms like Thalassia and Posidonia (low surface area to volume ratio). As you move from simple to complex, different evolutionary and ecological outcomes appear.

- On the left (high surface area to volume ratio), seagrasses are ephemeral, growing quickly during favourable seasons, but they are fragile and highly accessible to grazing. That means that almost all the material is consumed quickly, with little left over as detritus, and they don't stick around long enough for epiphytes to colonise. The consequence is a rapid turnover and open nutrient cycling; any unfavourable environmental change has rapid impacts on these plants.
- On the right (low surface area to volume ratio), species like Posidonia and Thalassia are persistent, long-lived, often surviving for many decades. They invest more energy into below-ground rhizomes for persistence, less into seeds. Nutrient and carbon turnover is slow—nutrients taken up are stored and remobilised when needed— and so they show a closed nutrient cycling strategy. They are resilient to many perturbations, but, if damaged, recover slowly.

In terms of ecological interactions, simple, ephemeral seagrasses are readily grazed; complex, persistent ones are tougher, less palatable. In complex forms, large amounts of detrital material can accumulate, resisting decomposition for long periods, and their persistence creates stable habitats, allowing rich communities of epiphytes, plants, and animals. The longer the structural tissues, such as rhizomes, remain, the more they can accumulate attached organisms.

8 Application and Closing Remarks

Surface area to volume ratio, then, has major consequences for the ecophysiology, distribution, and ecological interactions of plants and algae. Whether you look at terrestrial or marine environments, you'll see similar patterns: ephemeral, R-selected versus perennial, K-selected strategies. When you walk through nature, look for these surface area to volume ratio reasons for why different plants occupy particular habitats—often, the explanation lies in this fundamental geometric constraint.

There are some readings on ICOMVA for you, including some papers on surface area and volume ratios, as well as background on what seagrasses are. Remember, seagrasses are not true grasses; they look like grasses but represent a group of plants that have evolved on land and then returned to the sea—a separate evolutionary trajectory from seaweeds, which have always existed in the oceans. [Slide reference: left-hand side—Halophila as high surface area to volume, right-hand side—Posidonia sinuosa as low surface area to volume ratio. Note the presence of epiphytes on the latter.]

So, review this material, understand the consequences of surface area to volume differences, and their impacts across the spectrum of plant types and ecological circumstances. Be able to explain the consequences for distribution, ecophysiology, and ecological interactions.

Bibliography