Cambridge University Press
978-0-521-51804-8 - Reaching for the Sun: How Plants Work, Second Edition
John King
Excerpt
More information

Part I Plants and energy

'From dust you came, to dust you shall return,' is one sober, biblical reminder that complex organisms are built from simple chemical elements to which they will revert. From the beginning to the end of their lives, living things wage a battle against natural forces which break down their highly organized structure:

- At the cell level, complex molecules such as proteins and nucleic acids, to name but two of many hundreds, are continually destroyed by hydrolysis
- Valuable molecules are lost to the environment and have to be replaced because cell membranes are leaky
- Our atmosphere is dominated by the highly reactive molecule, oxygen, as a result of which everything on Earth, organic and inorganic, is subject to corrosive oxidation.

Yet, on all sides, we observe organisms using simple materials from their surroundings to maintain, renew, and build complex structures, to achieve which they need a constant supply of energy.

Organisms have evolved two ways of satisfying their absolute need for energy. The most crucial, **photosynthesis**, traps light energy from an outside source, the Sun, to fuel the building of complex organic structures from simple inorganic materials. The other, **respiration**, requires that there be a constant source from which chemical energy can be extracted and used for maintenance and construction.

Photosynthesis and respiration together comprise **bioenergetics**, how living organisms gain the supply of energy they need,which is the subject of Part I.

Cambridge University Press
978-0-521-51804-8 - Reaching for the Sun: How Plants Work, Second Edition
John King
Excerpt
More information

1 Photosynthesis: the leitmotiv of life

INTRODUCTION

Those who answer gardening questions from the general public will tell you that surprising numbers of people have a basic misconception about plants. The belief that plants build themselves from the soil is widespread even today, more than 300 years after proof showing this not to be so. Why such a belief still exists is puzzling. Consider the common practice of removing lawn clippings. If grass was simply built from soil, a lawn from which kilograms of clippings were removed during the growing season for the past dozen years would resemble a sunken garden, but it does not. Something additional to soil must go into building a plant.

PHOTOSYNTHESIS: THE KEY

We now understand that plants construct themselves from carbon dioxide (CO_2), water, and minerals with the aid of light energy. What plants make by this **photosynthesis** (putting together by light) is an endless supply of carbohydrates: sugars, starch, and cellulose.

Other green organisms can also photosynthesize

Plants are not the only organisms able to photosynthesize. Our oceans, lakes, and rivers are populated by a wide array of green organisms such as those algae which appear as green scum on ponds and lakes; the larger green, brown, and red algae, the seaweeds, found on or near seashores; and other microscopic organisms, the phytoplankton (certain bacteria, diatoms, dinoflagellates, and the smallest algae), which are especially abundant in our oceans.

Green organisms are sources of fuels

How plants and other photosynthetic organisms build themselves from a few inorganic substances is fascinating for practical reasons. Our oil and natural gas resources come from carbohydrates formed millions of years ago, mainly by ancestors of modern day ocean phytoplankton; ancient vegetation (mostly cellulose) is the source of our coal reserves; and plants and phytoplankton are also the primary sources of the foods that fuel the great majority of other living things.

How do they do it?

Attempts to understand how green organisms capture light energy, use it to split water, releasing hydrogen and oxygen, then use the hydrogen to reduce carbon dioxide to form sugars and other carbohydrates go back centuries. Today, given the problem of climate change, there is even a hope that we can find a way to exploit photosynthesis on an industrial scale to split water, giving us a supply of energy from a limitless, endlessly renewable, environmentally friendly source.

Understanding photosynthesis is, then, a matter both of curiosity about how green organisms do something so miraculous with such ease and because of its possible practical value as we phase out the use of fossil fuels such as coal, oil, and natural gas reserves. But first, a word about energy and its sources among organisms.

Energy: every living thing requires it

Energy drives everything that all living things do. As humans, we understand the need for energy to do physical work. Less obviously, we also need it for our brains to plan, or hope, or dream during sleep. Of the roughly 100 W of energy it takes to drive the entire human body, about one-fifth is used in activities of the brain.

Fuel and heat

The use of any fuel as a source of energy, whether it be in a car, a light bulb, a computer microchip, or a living organism, always leads to the production of heat as a byproduct. On average, about 90% of the energy in any source of fuel ends up as heat as the fuel is used. In warm-blooded animals like ourselves the production of heat is obvious. Less clear is the fact that heat loss occurs in all living organisms, whether warm to the touch or not, plants included. All organisms need fuel to replace this lost energy.

Sources of fuel – Antoine Lavoisier's great insight

One of the earliest explanations of the use by living things of fuel as a source of energy came from the eighteenth-century chemist, **Antoine Lavoisier**, when he wrote:

> Respiration [breathing] is merely a slow combustion [burning] of carbon and hydrogen, which is similar in every respect to that which occurs in a lighted lamp or candle, and, from this point of view, animals that breathe are really combustible bodies which are consumed.

Lavoisier's point was that animals had in them fuels containing carbon and hydrogen that could be slowly "burned" in respiration, releasing energy. This brilliant insight did Lavoisier not the slightest good. He was guillotined during the French Revolution, the judge allegedly dismissing him with the sentiment, "The Republic has no need of savants or of chemists".

Organic compounds

Today, we understand in a way not possible in Lavoisier's time that the thousands of natural chemicals found in living things contain carbon; most of them contain hydrogen as well. They were called **organic compounds** because it was thought at first that molecules containing carbon could be produced *only* by living organisms. We know now this is not so. Millions of organic compounds, many of which are artificial, are quite unlike any of their natural counterparts. They are still called "organic" because they all contain carbon; no other chemical element comes close to matching the diversity of compounds that carbon is capable of forming.

Carbohydrates

Carbohydrates, made up of carbon, hydrogen and oxygen, are among the most important fuels found in living organisms, and are "burned" in respiration to release energy. Those familiar to us are: **sugars** like **glucose** (grape sugar), **sucrose** (table sugar); **starch** (potatoes, corn, cereals, sorghum); and **cellulose**, the strong fibre from which the plant's basic structure is made, but as a fuel is less familiar since we, along with most other animals, cannot digest it. Only ruminant animals, such as cattle, sheep, and deer, and some others, like horses and termites, have adapted to the indirect use of cellulose as a fuel. All have bacteria in their digestive systems which can break down cellulose to a form the microbes can use as fuel. Animals harboring these microorganisms benefit by stealing the surplus fuel not needed by the bacteria while providing an environment in which they can prosper.

Glucose, the lowest common denominator

Before being used in respiration, sucrose, starch, and cellulose are all broken down to glucose. A molecule of sucrose contains one glucose and one fructose unit; starch and cellulose are made up of chains of hundreds of glucose molecules; all can be acted on by enzymes to release glucose.

BACK TO PHOTOSYNTHESIS

Making glucose from CO_2 and water in photosynthesis takes just as much energy as is released in "burning" it in respiration. There's no shortage of these two molecules in the atmosphere, oceans, lakes, the soil, and inside living organisms, but the chance of any of them coming together in the right way to produce even a single molecule of glucose is remote. Such an event is unlikely to have happened in the billions of years CO_2 and water have existed on Earth. The reason for this is that the chemical bonds holding hydrogen and oxygen

Cambridge University Press
978-0-521-51804-8 - Reaching for the Sun: How Plants Work, Second Edition
John King
Excerpt
More information

together in water molecules, and carbon to oxygen in CO_2, are extremely strong and must be broken before these two compounds can interact to form glucose.

SO … HOW DOES PHOTOSYNTHESIS WORK?

Green plants form glucose from CO_2 and water every daylight hour during the growing season. They then go on to produce a seemingly endless supply of sucrose, starch, and cellulose from the glucose. To appreciate more fully how plants do this so effortlessly, it is useful to know some of the history behind our understanding of photosynthesis.

The history

Lavoisier may have been one of the first to study animal respiration and to understand the need animals have for energy, but long before his day, it was understood that animals must eat to live.

Until some 350 years ago, it was thought that plants obtained their food in a similar way to animals, that is, by "eating" whole matter from the soil. Not only that, plants were also judged to have *perfect* nutrition since, unlike animals, they excreted no waste from what they "ate."

Also, the belief was that all things were made up of "the four elements" – earth, air, fire, and water. Air and fire were thought to have no weight and so it was considered that anything with weight could come only from either earth, water, or both.

Enter Jan Baptista Van Helmont

These early ideas began to change during the seventeenth century. In one of the first recorded scientific experiments, **Jan Baptista Van Helmont**, a Belgian physician, measured the growth of a willow sapling.

- He weighed it at the beginning and end of a 5-year period and found it had gained nearly 75 kg, yet, the soil in the pot in which the plant was grown lost only a few grams

- Van Helmont concluded that, therefore, the increase in mass of his tree could not possibly all have come from the earth in which it was grown since the soil lost only a tiny fraction of the weight gained by the plant.

But then Van Helmont made a mistake. He reasoned that if most of the weight gained by the willow was not from the soil then it must be from the water added to the tree during the 5-year experiment. He was a victim of the state of knowledge of the natural world at the time. As the elements water and earth were thought to be the only sources of bulk, it followed that if earth (soil) was not the source of the gain in weight of the willow, then it had to come from water.

Van Helmont was right in concluding that water contributed to the weight gain by his tree. His mistake was thinking that water was the *main* source of it. But what was particularly startling at the time was that the soil contributed so *little* to the weight gain. This inescapable conclusion changed for ever thinking about where plant food came from.

Farewell to "the four elements": alchemy and Joseph Priestley

There was no possibility of understanding Van Helmont's results until knowledge of chemical elements improved. Progress had to be made in thinking beyond "the four elements." At the forefront of these advances was the late eighteenth-century English clergyman, **Joseph Priestley**.

Combustion, or burning, was a topic that had intrigued alchemists for centuries, especially how one chemical compound could be transmuted into another by heat. The search for ways to transmute baser metals into gold or to produce the "elixir of life" are examples of the fascination alchemists had with the effects of combustion on substances. Modern day industries based on the purification of metals and their fusion together by heat to form alloys are outgrowths of the activities of alchemists, Priestley among them.

Injured and restored air

Priestley was fascinated by the "injuring" of air by combustion and performed some bizarre experiments to demonstrate it; for example:

- if he burned a candle in an air-tight container the flame soon went out;
- if he then put a mouse into the container, the animal died, because the air in the container, he concluded, had been "injured";
- he found, however, that if he put a sprig of fresh mint into an air-tight vessel containing injured air, the air was soon "restored" to a state in which it would "… neither extinguish a candle nor was it at all inconvenient to a mouse, which I had put into it."

In other words, the mouse did not die, was not "inconvenienced," as Priestley so delicately put it, as long as the air in the container was "restored."

Priestley did not see the light …

Priestley's conclusion was that vegetation "restored" air by cleansing and purifying it, removing the "injury." What he did not understand was that these restorative powers of plants depended on light. He used glass vessels in experiments so he could see what was going on inside but never did understand the significance of his choice.

… but Jan Ingen-Housz did

The importance of light in the "restoration" of "injured" air was left to the Dutch physician, **Jan Ingen-Housz**, to discover a few years later. He found air to be "mended" by vegetation only in sunlight and only by the green parts of plants. He also discovered that a plant absorbs the carbon in CO_2,

> throwing out at that time the oxygen alone, and keeping the carbon to itself as nourishment.

Light and air finally linked

Here was the first hint that light and CO_2 were linked in some way, leading to the release of oxygen, and that oxygen was the "restorative" in "injured" air. Here also was a hint that air provided a chemical element, carbon, to the nourishment of a plant. These, and similar, results made it clear that there was more to air than had been imagined. Perhaps it was, after all, possible to gain weight even from something so insubstantial.

We now know that Ingen-Housz was wrong in suggesting that oxygen comes from CO_2. In photosynthesis, it is released during the splitting of water.

Nicholas Theodore de Saussure connects the dots

One further essential observation was needed before the way forward to a full understanding of "synthesis by light" could be discerned.

The Swiss scientist, **Nicholas Theodore de Saussure**, made the final connection in the first decade of the nineteenth century. He showed that:

- in the light a plant released exactly as much oxygen as it absorbed carbon dioxide;
- equally importantly, he showed that the weight a plant gained was greater than could be explained by the amount of carbon taken in as CO_2.

In other words, in addition to CO_2, something else contributed to the solid substance of a plant. This extra contribution, de Saussure showed, had to be from water, since he was able to eliminate all other possibilities.

Van Helmont not so wrong after all

Water is critical to weight gain in a plant, but it is not the nearly exclusive source of the increase that Van Helmont had thought. Taken together, these early studies made it clear that the main bulk of plants could, after all, be produced largely from something as apparently weightless as air, in light only, with the help of water.

The realization of the importance of CO_2 and the need for sunlight for weight gain in plants shifted attention in the study of photosynthesis away from the soil to where it belonged, to the role played by the atmosphere and by light.

LIGHT AS ENERGY SOURCE

The heat of summer and sunburn remind us that there is no lack of energy in sunlight.

- The amount of solar radiation reaching Earth each year is about 4×10^{18} joules (4 exajoules).
- The amount arriving at our planet each hour, some 4×10^{14} joules, is more than enough to satisfy the world's energy needs for an entire year.
- About 60% is reflected directly back into space (recall the images of the brilliant, shining planet Earth as seen from outer space); most of the rest is absorbed by the atmosphere, by clouds, or by oceans and landmasses and promptly re-radiated back into space as heat.
- The amount of sunlight absorbed by green plants and used in photosynthesis is tiny, no more than 1% even of the fraction of solar energy that penetrates to the planet's surface.

ABSORPTION OF LIGHT

Since the late nineteenth century it has been known that, when light is absorbed by metals, electrons are dislodged from them and can be organized into an electric current; solar panels operate on this principle.

Plant pigments

In a plant, light is not absorbed by metals but by **pigments**, molecules whose bright colors signify that they strongly absorb only some of the wavelengths of visible light. The dominant pigment found in plant leaves is chlorophyll, which absorbs the blue and red wavelengths of light; wavelengths which are reflected from the leaf or pass through it give the pigment its characteristic green color. Several other pigments are also found in most plants but cannot be seen until the autumn when chlorophyll disappears from leaves. All of these pigments absorb bluish–violet light so we see them as being yellow, orange, or red, depending on which wavelengths they absorb (see Chapter 11 for a discussion of plant pigments and color, and Chapter 9 where a quite different pigment, phytochrome, is described).