11

PLANT BIOLOGY

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Introduction

John King (1997) has observed that "without green plants, the earth would be a stark, largely lifeless place" (p. 215). Consequently, how green plants contribute to life on earth needs to make sense to its human citizens. In this chapter, we draw attention to the importance of "reading the story" (Bromham, 2008) of plant contributions to life on earth through the approach of 'big ideas' (Harlen et al., 2015; Matthews, 2009; Uno, 2009) in biological science. The core concept directing our chapter is the role narratives can play in students' experiences of science education (Bromham, 2008; Avraamidou & Osborne, 2009), and the professional development of teachers. We suggest that realigning the position of plants from isolated characters in school biology to central actors working across a storied landscape of a 'big idea' could radically alter students' conceptions of plant science, and the essential role plants play in the wider world, particularly in addressing some of the current global challenges, such as climate change and food insecurity. We believe that it is necessary, when teaching, to highlight the 'big ideas' of biology to our students as a synoptic narrative. Thus, in this chapter, the role of photosynthesis in plants as enabling life on earth is our example big idea, as affirmed by the following authors:

> Photosynthesis is a fundamental process for life on earth, with many biologists rating it *the* most important natural process.
>
> *(Matthews, 2009 p. 929)*

> We are currently cultivating one-quarter of the total land area, and we are currently, consuming, in one way or another, 40% of all photosynthetic activity.
>
> *(Walker, 2012, pp. 91–92)*

In an educational context, Uno (2009) cites the dual issues of biology textbooks not using plants and trainee science teachers receiving little plant biology education in their training. We suggest a conceptual and didactical gap can arise as a result of this absence. Moreover, perceptions of plants as passive bystanders to environmental change—Beerling's "silent witnesses" (2007, p. 1)—can further diminish student and teacher appreciation of the complex world in which plants exist, no less so than when teaching and studying photosynthesis.

Energy for Life

Photosynthesis is a complex and somewhat abstract process that is often taught in a series of incremental modules beginning with 'plants can make their own food' in primary school and continuing to advanced level equations which are a "summary of some 30 separate steps" (Reiss, 2011, p. 54), in upper secondary school. Indeed, it is a subject often oriented around a series of textbook equations increasing in complexity as a child moves through their schooling. Unlike the topic 'plant adaptation', which is best taught in the physical presence of plants, photosynthesis can be taught without access to living material. Thus, the process of photosynthesis can be perceived by students as abstract, repetitive and disassociated from wider biological processes and, as such, misconceptions abound. Furthermore, the complexity of photosynthesis, with its connections to physical, chemical and biological processes, can make plants look *difficult*. Although all these processes are seen as *biology*, exploring the ideas behind photosynthesis includes:

- Comprehension and acceptance of significant areas of understanding within physical science processes of energy transfer, excited states of pigments and accessory pigments.
- An understanding of wavelengths of light and chemical processes of the reactions, including reduction of compounds to provide energy 'storage' and the complex biochemistry of an array of carbohydrates.
- An understanding of a suite of organelles, cells, tissues, transport systems, enzymes and proteins and the biochemistry of sugars.

We suggest that these complexities and technicalities, when taught through a biological topic called photosynthesis and led by a content testing curriculum, contribute to the loss of the awe about the truly amazing feat of nature that is photosynthesis (Morton, 2007). Given the critical role of photosynthesis as a "fundamental process underpinning life on earth" (Matthews, 2009, p. 929), we believe student understanding of this process is an important part of scientific literacy and, as such, needs to be experienced in ways that foreground photosynthesis as a central biological process, particularly as "living within our biological means is an important issue that will not go away. Photosynthesis is the only way of providing us with our daily food, and so much else" (Walker, 2012, p. 103). In the next section, we focus on relevant studies of students' misconceptions in this area, as a background to our proposed narrative-based approach to teaching photosynthesis, and plant science more broadly.

Student Misconceptions

Lin and Hu (2003) report their research concerning 12- and 13-year-old student understanding of energy flow in biological systems and the linking between the living and non-living worlds, and between different levels of complexity in biology that they base on work by philosophers of biology. Lin and Hu (2003) identify these levels as "phenomenal knowledge" at a whole organism level, "mechanical knowledge" at a cellular level and "physical knowledge" at a molecular level (see Lin & Hu, 2003, p. 1530). Their research demonstrates that students find it hard to link the different levels of biology, especially using ideas of physical knowledge about energy and matter, in their explanations of photosynthesis and respiration. In addition, Marmaroti and Galanopoulou (2006) show that although some students may answer that light or chlorophyll is needed for photosynthesis, they do not always then link this with photosynthesis occurring during the day or under artificial light, or in the green parts of plants.

Ryoo and Linn (2012) consider energy transformations to be critical to understanding photosynthesis and that, as rather an abstract concept and one that is invisible, it is hard for students to understand in any context and may be new to students who are expected to learn about photosynthesis. They also recognise the problem of textbook presentations that inadequately explain, in writing and diagrams or equations, the role of light energy in the process.

Uno (2009) supports the assertion of Lin and Hu (2003) that coherence of understanding between different levels of organisation are important and that teaching using overarching 'big ideas' could be the way forward, e.g. including evolutionary biology in teaching about photosynthesis so that students understand how, and why, chlorophyll developed and its importance in plants making food. Uno (2009) also acknowledges that students' alternative conceptions can be hard to change and should be investigated at the start of a teaching sequence by asking diagnostic questions (or "concept inventories", p. 1755). These are issues, we suggest, that can be approached through teaching strategies designed to encourage conceptual linking between the overall picture and what makes photosynthesis happen. Thus, our recommendations for teaching respond to Uno (2009) by offering models for teachers to develop "concept inventories" (p. 1755) through "historical vignettes" (Clary & Wandersee, 2015; Wandersee & Roach, 1998) and "concept cartoons" (Keogh & Naylor, 1999; Keogh, et al., 2001) as narrative-based activities working alongside seeing the process in action practicals (Jenkins, 2015). This, we suggest, is an approach with which to develop the knowledge levels outlined by Lin and Hu (2003).

Difficulties in Teaching About Plants

Many of the documented difficulties concerning human attention to plants originate from the perceived *otherness* of their physical form and behaviours, as indicated in the extract below:

> Plants are curious organisms—clearly, they are alive but their apparent lack of any central organization (brain, heart, or nervous system) makes it harder for us to understand how they work. They are slow: usually they look today just like they did yesterday and we have to wait, sometimes a long time, to see changes in them.
>
> *(Van Volkenburgh, foreword in Koller, 2011, p. xiii)*

However, these characteristics also offer opportunities. Numerous cellular processes in plants operate at similar rates to their zoological counterparts providing us with ample opportunities to demonstrate many key biological processes, and indeed experiment upon them as models for living organisms more generally. This is emphasised by their use in common practical investigations in the school laboratory, e.g. investigation of osmotic potential on tissue (potatoes), source of enzymes in rate reactions (leaves) and the source of material for lower secondary introduction to cells using microscopes (onion). Yet, this specific use in practical investigations does not always translate into a broader picture of the contribution plants make to biological science, nor to their role in enabling life on earth. Slingsby (2006), for example, has criticised the role of plants in school biology as being reduced to "victims in a series of photosynthesis experiments that don't always work" (p. 51).

If this bleak experimental landscape is adjoined to limitations in teacher and student engagement with plants (Uno, 2009, Nyberg & Sanders, 2014), an emergent problem for society becomes visible. Understanding the contribution of plants to biological life is vital in an era in which plant extinction numbers are increasing (Willis, 2017) and the climate is changing, much of which is attributed to human activity.

Plant-Blindness

The role of plants in the received curriculum is frequently perceived as separate from animals, and often focused on specific *plant topics*, a classic case being that of photosynthesis. Additionally, the planned curriculum often uses animal-based examples for biological concepts (Nantawanit et al., 2011;, Nyberg & Sanders, 2014). In the context of plant science teaching and learning, Ebert-May and Holt (2014) have observed that "plant blindness exists—we need to know the cognitive underpinnings and instructional design that enables students to 'see' plants" (p. 362). In addition, Balding and Williams (2016) suggest that "it is likely that both biological and cultural factors shape human-plant relationships" (p. 3). In response, we believe that 'plant blindness' is but one of the influences on teacher choice. In the planned curriculum, there are many opportunities for teachers to choose which living material to use, and hence create a less zoo-centric focus. For example: why, in enzyme practical investigations, do teachers use a source of catalase from mammalian liver as opposed to potato or other plant tissue? Or why, in the discussion of medicines from plants, is the focus on the product used in human treatments but the purpose in plants often ignored?

Being rooted in one place requires plants to develop highly sophisticated capacities to respond, communicate and react to external stimuli, physical attack and competition with others, develop mutualistic partnerships and, ultimately, reproduce. In addition, the ability of plants to photosynthesise makes them a critical component in food webs and thus important in discussions of food security. Moreover, the intransient nature of plants makes them vulnerable to climate change impacts in relation to pollination vectors, flowering times and habitat needs. Teachers need to be familiar with the science behind these statements—a challenging familiarity if the teacher has neither studied plant science as their biology major nor experienced in-depth plant science in their teacher-training (Uno, 2009). Furthermore, curriculum frameworks often focus on the zoological side of biology; hence, students might make assumptions that plant science has little relevance to contemporary scientific research. As useful models for experimentation in biology, numerous 'firsts in science' (Sainsbury Laboratory University of Cambridge, 2017) were discovered using plants, including:

- *Cells (1655)* Microscopic observations of thin sections of cork led Robert Hooke to discover cells, the building blocks of life.
- *The principles of genetics (1866)* Gregor Mendel's experiments with pea plants allowed him to formulate the basic rules for genetic inheritance of traits.
- *Transposons (1948)* Barbara McClintock used genetics and observations of maize chromosomes to discover transposons, sometimes called jumping genes. These are bits of DNA that move about the genome and can influence the expression of other genes.
- *Totipotency of cells (1957)* Using tobacco cell cultures, Folke Skoog proved the idea proposed by Gottlieb Haberlandt that adult cells could give rise to all cell types. This is the fundamental basis for stem cell biology.
- *Post transcriptional gene silencing (1990s)* The discovery that extra copies of a gene introduced into the genome can trigger silencing of both the introduced and endogenous gene was made first in petunias. The mechanism involved was later shown to involve small RNAs.

Likewise, recent scientific papers, such as Jennings et al. (2010) and Schöner et al. (2017), offer evidence for, in the case of Jennings et al., competition between a carnivorous plant and a spider for the same prey and, in Schöner et al., a pitcher plant benefitting from transferring the pre-digestion of prey to a bat mutualist. These scientific narratives represent the dynamic interconnectedness of the living world and offer contemporary sources for teachers and their students to examine the often complex ecological relationships between plants and animals.

In the context of science education research, Nantawanit et al. (2011) have found that students enjoy "the secret stories of plants" (p. 850) as active constituents of ecosystems, which in their work focused on plant defence strategies. Furthermore, Ebert-May and Holt (2014) note that "thinking of plants at multiple scales requires understanding of core ideas (evolution and ecology), cross-disciplinary concepts (matter and energy), and use of science practices (models, arguments, and cooperative work)" (p. 361).

Returning now to the teaching of photosynthesis, we suggest that using a combination of practical investigations, historical vignettes and concept cartoons offers teachers and students a synoptic approach that brings together seeing the process in action, talking through "conceptual inventories" (Uno, 2009) and knowledge building in multiple ways (Ebert-May & Holt, 2014).

Recommendations for Teaching About Plants

Photosynthesis: Seeing the Process in Action

An approach central to many teaching schemes covering photosynthesis is using practical experimentation to demonstrate the process in action. Two classic demonstrations of the process are commonplace—testing a leaf for starch and observation of bubbling aquatic pondweeds. These activities enable the development of a sense of awe at the process (Jenkins, 2015) and go some way to demonstrate the abstract equations for the process in action. However, these classic examples have limitations and can introduce misconceptions; below, we discuss alternative practical procedures to demonstrate photosynthesis in action that overcome some of these difficulties.

Testing a Leaf for Starch

Barker and Carr (1989) described how many students do not understand the starch test, struggle to understand the complex mechanics of the test and cannot link the presence of starch to photosynthetic activity. They note that one student thought starch was produced when chlorophyll and iodine mixed together. In addition, Kinchin (2000) discusses use of the starch test as proof of photosynthetic activity as problematic; there are numerous examples where starch is present in plant tissue in areas unrelated to photosynthetic activity (e.g. potato tubers found underground). The above issues are then confounded by acknowledgement that the point of demonstrating the presence of *starch* as proof of photosynthetic activity doesn't meet the standard equations for photosynthesis presented to students showing *sugars* not *starch* as one of the end products.

Bubbling Pondweed

This demonstration of photosynthesis in action focuses on the other main product in the generalised equation for photosynthesis, oxygen. However, as many educators attempting this classic demonstration of photosynthesis (first developed by Jan Ingen-Housz in 1779; Ray & Beardsley, 2008) discover, reliability of this method as a quantitative measure of the rate of photosynthesis is full of problems. Mostly these are down to the selection of an appropriate pondweed to 'bubble' reliably and on demand (see Jenkins, 2015).

Both bubbling pondweed and the starch test can be useful as pupil assessment tools; however, Eldridge (2004) notes that when used to demonstrate photosynthesis, these practical investigations do "little to improve student understanding of the whole process" (p. 37). Therefore, discussion with the student is needed on the abstract elements of this as a demonstration of photosynthesis in action. The convention when teaching the evolution of oxygen as a product of photosynthesis involves leaves and stomatal pores in a scenario operating in the open air. However, we introduce an added level of complexity transposing this process into an aquatic plant, which is inverted to collect gas from the cut stem, all operating under water. Through this practical there is potential to introduce a disconnect between the site of photosynthesis discussed with students (leaves) and the collection of the products (from an inverted stem, underwater). The source of carbon dioxide (normally from the air) is often not mentioned, and the fundamental importance of the process (capture of energy and carbon storage products) may be lost to the student. Recognising that dissolved carbon dioxide (present as carbonic acid) is the source of carbon for photosynthesis in aquatic plants enables a discussion with students on the opportunities to measure both reactants and products (Ray & Beardsley, 2008). pH can be used as a proxy for carbon dioxide measured using an indicator present in the water and products (bubbles of gas produced) measured during photosynthesis.

Observing Photosynthesis and Respiration in Plant Material

The misconceptions that photosynthesis is the opposite of respiration and that respiration happens at night and photosynthesis during the day are common. To help explore these misconceptions, several teaching schemes introduce using hydrogen carbonate indicator to demonstrate changes in level of carbon dioxide accompanying respiration and photosynthesis.

Sections of aquatic plants can be put into vials of pH sensitive indicator. In the presence of sufficient light, over time this demonstrates the 'use' (i.e. decrease in concentration) of the reactant carbon dioxide. This is visualised by a colour change in the indicator. In low light levels or in darkness, the same system demonstrates the effects of respiration, increasing carbon dioxide levels (see, for example, Eldridge, D., n.d.).

Using the indicator also provides an opportunity to discuss and introduce the compensation point between photosynthesis and respiration in terms of net carbon dioxide levels. The concept of this balance helps learners understand that respiration is always occurring in plants.

Eldridge (2004) introduced a new procedure to observe and quantify photosynthetic rate in green algae and suggested

> the use of immobilised green algae as photosynthetic organisms which are easy to manipulate. Students may then determine the rate of carbon dioxide absorption by the algae using hydrogen carbonate indicator and a colorimeter or colour scale. In addition, the importance of carbon dioxide as a requirement for photosynthesis is emphasised in an implicit way, as students are in effect taking measurements of how much carbon dioxide is taken up by the algae, which causes the change in the colour of the indicator.
>
> *(p. 38)*

This procedure has been widely adopted by many teachers across the UK and was incorporated into the Strategies for Assessment of Inquiry Learning in Science project materials (www.sails-project.eu) as a more reliable investigation to quantifiably investigate photosynthesis in action. It overcomes the core issue of unreliability of bubbling found when using pondweeds. The algae gain protection from being immobilised in alginate so, unlike a cut section of pondweed, 'algal balls' will continue 'working' in the system for several hours. Once immobilised, the algal balls can be kept for future investigations, allowing a focus on photosynthesis or respiration. Guidance on preparing and using immobilised algal balls as initially outlined by Eldridge (2004) can be found at www.saps.org.uk/algalballs.

Photosynthesis: A Narrative Approach

We agree with Matthews (2009) in his foregrounding of photosynthesis as a 'fundamental process' in biological science; moreover, this is a topic in which students struggle, as previously outlined. Therefore, in this section we focus on narrative-based ways to complement seeing the process in action through practical experiments. Both of the suggested narrative methods attempt to overcome misconceptions held on the topic of photosynthesis using student-centred approaches, which work to make explicit alternative conceptions held by students. By attempting to draw out students' own views on the chemistry, physics and biology concepts involved, these approaches begin to tackle the complexities noted by Lin and Hu (2003), and are influenced by narrative-based approaches to science education (e.g. Avraamidou & Osborne, 2009).

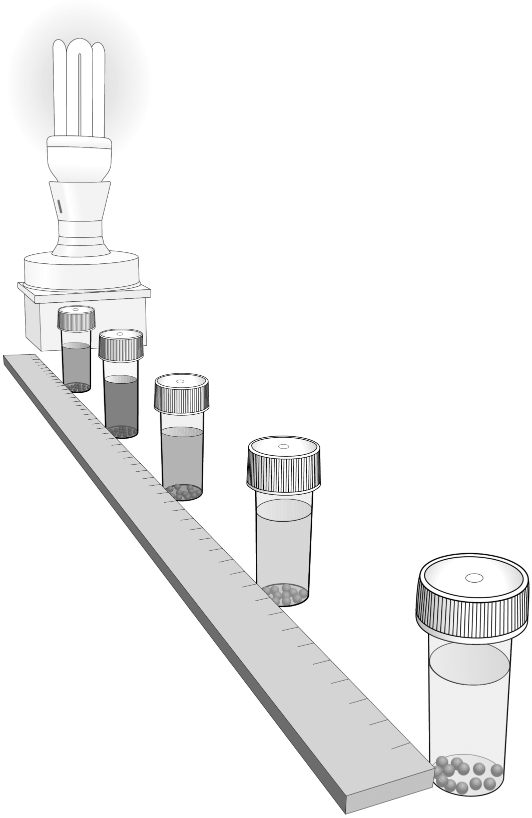

FIGURE 11.1 Immobilised algal balls in hydrogen carbonate indicator.

Credit: National Centre for Biotechnology Education, University of Reading. Drawn by Dean Madden.

Historical Vignettes

In this section, we discuss the use of 'historical vignettes' (Clary & Wandersee, 2015; Wandersee & Roach, 1998) in the context of the experimental history of photosynthesis as a narrative-based model with which to record, in a teaching context, students' alternative conceptions concerning photosynthesis.

Example: *'Where does the wood come from?'*

Using historical work carried out by Jean Baptiste van Helmont in the sixteenth century, students examine their views on 'where does the wood come from?' After reading an extract from van Helmont's diary, students discuss his interpretations. Four typical student responses to van Helmont's experiment are given in the speech bubbles in Figure 11.2.

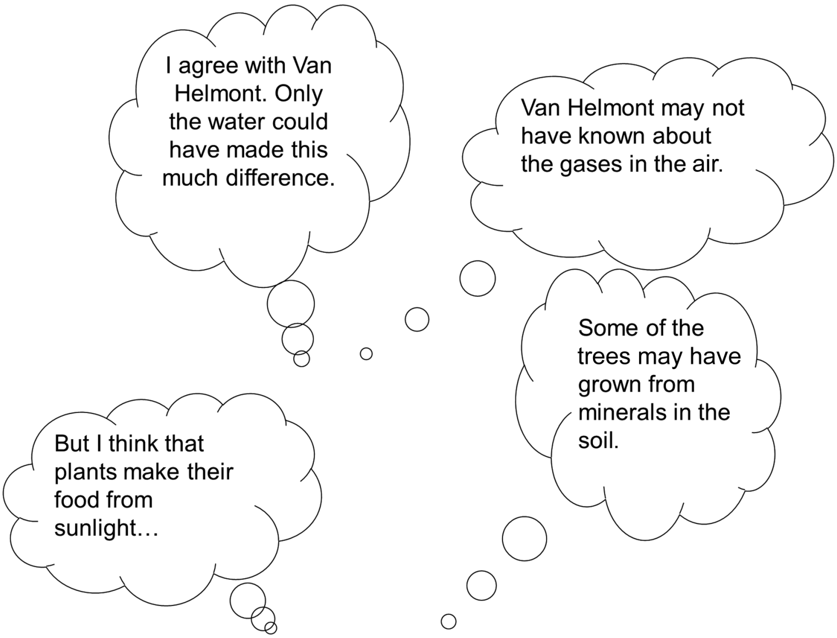

FIGURE 11.2 Where does the wood come from? Eldridge, D. (n.d.). *Where does the wood come from?* Retrieved from www.saps.org.uk/secondary/teaching-resources/134.

Credit: Science & Plants for Schools, University of Cambridge.

Students are given cards as a stimulus to talk in structured groups about each of the statements and examine data and pictures of more recent experiments. They summarise their thoughts and feed back to the rest of the class. Throughout the discussion it is important to introduce and reinforce the idea that an increase in mass (biomass) is good evidence that photosynthesis has taken place and that carbon dioxide from the air contributes to this.

By acknowledging the biological, chemical and physics processes involved in photosynthesis, this teaching scheme attempts to recognise some of the abstract elements of photosynthesis. The work scheme continues to explore how carbohydrates are made and helps teachers redress the commonly held misconception that the mass of a plant comes from the soil. It is worth noting that van Helmont believed water was the source of the accumulation of mass in a plant, not carbon dioxide. Discussion of this with students presents another opportunity to acknowledge and explore alternative conceptions, their presence and importance throughout the history of science.

Using historical characters alongside original student thinking enables students to find that their conceptions of the seemingly counter-intuitive and abstract process of photosynthesis are justified. By exploring the historical development of our understanding of photosynthesis, alternative conceptions can be voiced and appropriate conceptions then scaffolded by the teacher working alongside their students, for:

> Not only does history facilitate understanding of the nature of science for our students, but it also provides historical analogies of modern topics, enabling our students to develop useful research skills, effective scientific argumentation, and better scientific understanding.
>
> *(Clary & Wandersee, 2015, p. 329)*

Van Helmont is not the only historical character to be used in these 'historical vignettes'. Matthews (2009) has written at length on the attributes of working with Joseph Priestley and his photosynthesis investigations and concludes that "Priestley is an under-utilised figure in science education" (p. 955). He goes on to note:

> Unfortunately, Priestley's contribution to the modern understanding of photosynthesis is seldom mentioned in school curricula. This is a pity as his role was pivotal, and students can very easily be led through many of the same steps that he took.
>
> *(Matthews, 2009, p. 955)*

Matthews' (2009) statement suggests the use of historical vignettes alongside replications of Priestley's investigations, without, we suggest, causing distress to a mouse.

Concept Cartoons

One of the biggest challenges for teachers of all subjects is how to bring student voice into lessons in ways which a) are meaningful and authentic and b) help students to voice their uncertainties as well as express their "islands of expertise" (Crowley & Jacobs, 2002). Concept cartoons are a response to this challenge:

> Concept cartoons extend the range of pedagogical strategies available to teachers. They present learners with a set of alternative ideas about a scientific concept in visual form. They are used mainly in the classroom to support teaching and learning in science by generating discussion, stimulating investigation and promoting learner involvement and motivation.
>
> *(Keogh et al., 2001, p. 137)*

Within a carnivorous plant education programme, which one of us developed in 2012, the students are asked for their views on plant nutrition, using Figure 11.3 as a stimulus for student reflection to aid teacher diagnostics or "concept

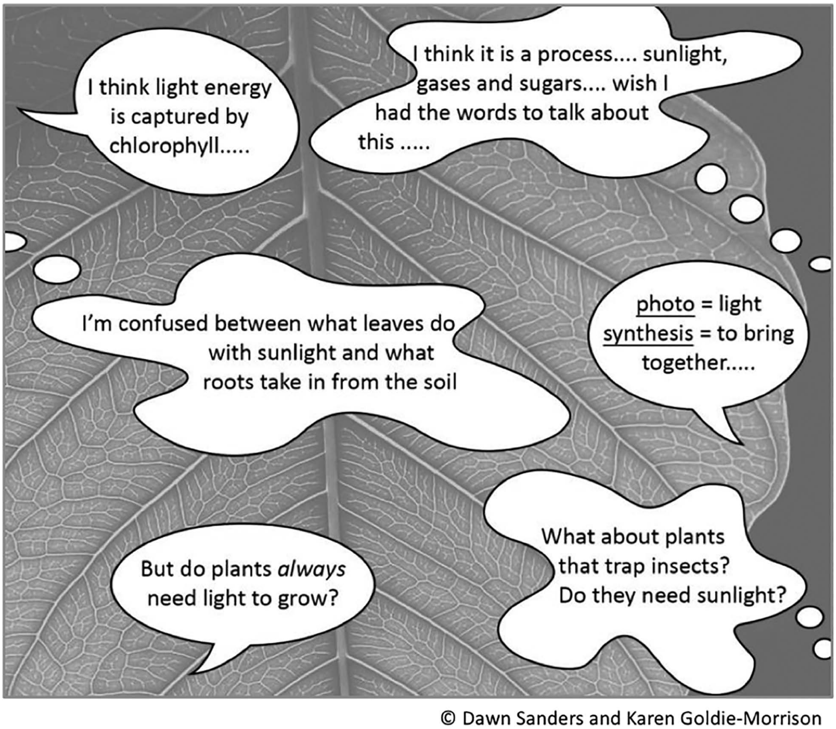

FIGURE 11.3 Concept cartoon from *Murderous Plants*.

Credit: The Charles Darwin Trust. Reproduction Permission Linnean Learning.

inventories" (Uno, 2009, p. 1755). The student speech and thought bubbles are drawn, in part, from the research of Driver et al. (1994) on secondary students' understandings of photosynthesis. More specifically, students can connect with the represented thoughts, theories and ideas. The notion behind this multimodal representation is to support student confidence in publicly discussing their internal uncertainties when represented as an external voice in a teaching aid, and to fulfil Keogh et al.'s (2001) recognition that

> an effective auditing strategy will both diagnose the students' level of understanding of science concepts and help them begin to reconstruct their understanding.
>
> *(p. 138)*

Thus, the concept cartoon, used in this way, can act as a proxy for internal dialogues, previous learning experiences and tentative ideas, in order to decentre individual performativity and instead facilitate group discussion, aided by the teacher's didactical moves.

Conclusions

We have presented a case for teaching plant science in the secondary curriculum using the 'big ideas' approach to school biology affirmed by Uno (2009) and Harlen et al. (2015). In so doing, an assemblage of teaching approaches, in which student-centred learning complements practical experiments, has been suggested for one strand of plant science, namely the process of photosynthesis. Our teaching recommendations are a response to a body of research literature on student misconceptions and common didactical moves, and the documented limitations of standard practical investigations. These suggestions for teaching photosynthesis can be readily applied to other biological science arenas, examples of which include ecosystems, respiration, modern genetics and evolution.

Modern plant science is a complex arena of practices from computer modelling to field-work (Jahren, 2016; Woollard, 2017). At the heart of this science lies an incredibly diverse kingdom of life forms. School biology cannot hope to replicate such complexity, but what it can do is provoke awe and wonder in the presence of plants and the significant biological processes they underpin. We suggest that teaching that combines seeing the process in action through practical work with historical narratives and concept cartoons will assist students to 'read the story' (Bromham, 2008) of the vital contributions plants make to life on earth, through their "noble and important services" (Hales, 1727, p. 324).

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