Handbook of Research on Mobile Devices and Applications in Higher Education Settings

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Chapter 7
The Global Change App:
The Creative Transformation of Scientific Research

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ABSTRACT

The global carbon and water cycles, and the process of photosynthesis are integral components of any high school science class or university science degree. Despite being intricately linked, these important global processes are often taught in isolation. This disconnection can lead to students having an incomplete understanding of the interconnection of leaf level processes, global cycles, and how they are affected by human activities. The "Global Change" app is an interactive teaching tool that illustrates how the biotic and abiotic systems involved in carbon and water cycling are connected to the stomata, and how human activities are affecting these processes in a meaningful way for students. In this chapter, the authors identify key gaps in students understanding and explain how the app addresses these. Example lessons are provided that encourage student self-inquiry, in a way that allows flexible, interactive learning. The Global Change app demonstrates how creative design and science can be combined to enhance the engagement of students with complex scientific concepts.

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INTRODUCTION

Knowledge about the carbon and water cycles are critical scientific concepts for participating in global climate change discussion. Without an understanding of these cycles and especially comprehension of how human activities impact on these cycles, students lack “preparedness for life” in society (OECD, 2006). Nevertheless, there are still several difficulties in understanding the evidence for climate change not only in students but also in adults (e.g. Robelia & Murphy, 2012). Thus, learning about the global processes and how they are influenced by human activities from a social perspective is a highly relevant topic for students. The *Global Change* app (hereafter “the app”) integrates complex scientific concepts of these ecological processes with design and animation; placing an interactive learning environment to teach these concepts at the fingertips of students and lecturers via their mobile devices. The app is free to download from the iTunes and Google Play stores. In addition, there is a PC version that is ideal for lecturers to use in a classroom setting. The app provides an overview of the physiological function of stomata; the terrestrial interface for the carbon and water cycles, the major components of the carbon and water cycles as well as the main global change impacts that are acting on them. The aim of the app is for it to be used as a teaching support tool for illustrating how the biotic and abiotic systems involved in carbon and water cycling are connected to the stomata, and how human activities are affecting these global processes in an approachable and meaningful way for students. In addition to the embedded content, the app links to external information, including open access peer-reviewed literature; where both students and lecturers can further explore concepts with scientifically robust information to enhance understanding of the connection between the natural world and human activities.

The app is a prime example for teaching scientific literacy, which aims to improve students’ understanding of scientific principles and processes that will enable personal decision-making, and students´ participation in discussions of scientific topics that affect socio-scientific issues (e.g. National Science Education Standards, 2006). The ability of students to make use of these competencies depends on the students´ scientific knowledge, i.e. their content knowledge of the natural world (e.g. carbon and water cycle are connected through stomata), their procedural (e.g. procedures used by scientists to establish scientific knowledge), and their epistemic knowledge (e.g. to understand the reasons for common practice of scientific inquiry (OECD, 2015)). The purpose is not to offer any new information about either cycle or the role of the stomata in the interactions between the cycles; rather, the app provides an interactive educational platform for teachers, students and non-climate-scientists. This chapter provides an overview of the capacity of educational apps on mobile devices, such as *Global Change* to address known students’ knowledge gaps or learning demands about the complex processes of photosynthesis, respiration and the links between the natural world and human activities.

Background

The process of photosynthesis converts carbon dioxide (CO_2) into sugars and photosynthates that are used to increase biomass, exchanging oxygen and water molecules as by-products back into the atmosphere. Photosynthesis is arguably the most fundamental biochemical process on earth, without it life as we know it simply would not exist. Rates of photosynthesis are directly related to transpiration; the biologically mediated movement of soil water through the vascular system of plants, and the transfer of carbon (respiration) to and from (photosynthesis) the atmosphere, which are regulated by the same organs, the stomata (Ferguson & Veizer, 2007).

In general, students are familiar with these key ecological concepts; however, they often show difficulties in apply these on an ecosystem or global level. Several studies have shown that students of all age groups have conceptions that differ with the scientific explanation about the processes of transpiration (Yip, 2003), cellular respiration and photosynthesis (Songer & Mintzes, 1994; Cãnal, 1999; Parker et al., 2012), as well as about cycling of matter (Leach, Driver, Scott, & Wood-Robinson, 1996), and system thinking in general. For example, Sibley et al., (2007) found that US-students of a general geology course had difficulties to recognize all parts of global biogeochemical systems, especially those that are not readily visible (e.g. groundwater). The authors described that the students had a limited understanding of condensation, when asked to fill in a water cycle diagram (including three different phases, i.e. solid, vapour and liquid, and at least three different locations). Students omitted condensation between water vapour in the atmosphere and precipitation (Sibley et al., 2007). The authors argued that students need four basic abilities to apply a system thinking approach to understanding the water cycle:

1. To identify substances, locations of substances and processes between the systems,
2. To organize the substances and processes within different frameworks (e.g., box diagrams),
3. To understand and to explain the cyclic nature of a system, and
4. To recognize parts of a system that are not readily apparent (Sibley et al., 2007).

Other studies show that students of different age groups have difficulties in understanding key processes in ecology. A specific student conception, for example, is that photosynthesis is the inverse respiration of plants or in other words that photosynthesis is the plants' form of cellular respiration (Cãnal, 1999; Songer & Mintzes, 1994). Within this conception is that photosynthesis takes place during the day, and that plant respiration occurs only during the night (Marmaroti & Galanopoulou, 2006). Besides photosynthesis, respiration is a difficult topic to grasp for students. Even practicing and trainee primary teachers admit they have uncertainties when explaining the role of carbon in the processes of decay and of manufacture of tissues in animals and plants (Summer, Kruger, & Childs, 2001). Especially the question how carbon is released to the atmosphere during decomposition was difficult to answer for one of the study groups. The same holds true for misunderstandings about the cycling of carbon through the biosphere (Summer et al., 2001). With respect to the global carbon cycle and imbalance caused through human activities Niebert and Gropengießer (2012) identified several misunderstandings in 18-year old German students. For example, the authors describe student conception of "natural vs. manmade CO_2" which elucidates the fact that students think that CO_2, which is emitted by human activities has a different structure than CO_2 emitted by respiration, and thus that it cannot be fixed by photosynthesis again. According to the students´ understanding, manmade CO_2 remains in the atmosphere and leads to increasing CO_2 concentrations. This proves that students have difficulties to recognize that climate change is caused by imbalanced carbon fluxes and that thinking in fluxes between atmosphere, oceans and land biosphere is difficult for students (Niebert & Gropengießer, 2012).

Human activities are increasing carbon dioxide levels in the atmosphere, which causes surface temperatures to rise, affecting water availability to plants. On the other hand, the additional CO_2 also affects stomatal opening directly via enhanced photosynthesis rates. The effects of changing environmental variables on the physiological function of stomata are described in the app in a way that connects leaf level process to the global cycles in an albeit simplistic way, where students can build on this base knowledge to gain a greater understanding of more complex processes using a systems thinking approach. Further, environmental parameters such as temperature, humidity, carbon dioxide, and light cause stomata to either open or close, affecting the flux of carbon and water between the terrestrial and atmospheric pools. These processes are described in simple terms in the app. The first three drivers of stomatal control (temperature, humidity, and carbon dioxide) are common components of the climate change discussion, which helps students to think about the linkages between human activities and the physiological function of stomata and in turn, the global carbon and water cycles. The connections between leaf level processes, biogeochemical cycles and the influence of human activity on the natural world is the fundamental framework the app is based on, with the ultimate goal to facilitate system thinking in students using mobile devices.

MAIN FOCUS OF THE CHAPTER

Smart devices are ubiquitous in the hands of most students, using such tools as a means of engaging students for learning, rather than tools of distraction provides an opportunity to take advantage of evolving learning pathways. As Avraamidou (2008) notes, mobile devices and creative scientific apps can be seen as *tools for thinking,* that are used to promote collaboration, expression of ideas and discourse among students, tools for modeling cause and effect relationships, tools that scaffold complex investigations, and tools that enable students to visualize complex scientific phenomenal (p. 351). This chapter identifies key gaps in students' understanding of the global carbon and water cycles and how human activities are influencing these cycles, outlines how the content of the app addresses these conceptions, and explicates the role of mobile devices as an increasingly fundamental teaching tool. The authors provide examples of learning pathways that lecturers can use in the classroom to facilitate students' understanding using their own smart devices. The instructional strategy is to guide the students through the app by linking the stomata with the global carbon and water cycles and making cognitive connections about how human activities are influencing these biogeochemical processes. The authors emphasize that the app is designed so that users can explore the global carbon and water cycles in a multidimensional way. These examples of learning pathways illustrate the flexibility of apps, such as the one presented here, can be used in a variety of curricula, from high school science classes to tertiary institutions. Such flexibility allows lecturers to diversify their teaching style, and students to explore information independently while still in a supportive classroom setting. Further, learning pathways can be a collaborative and creative process for both lecturers and students in order to initiate system thinking in any curricula.

Issues, Controversies, Problems

The evolution of technologies for learning has been accompanied by innovation in the ways in which content is redesigned and repurposed for the affordances of new media. The advent of film and television afforded new dimensions of understanding science for educators, where complex scientific concepts could be explained in formats that went far beyond the limitations of the printed page and classroom chalkboard. The personal computer, together with advances in processing power and software design, saw further advances in multimedia development and the increasing facility for educators to design engaging applications in collaboration with designers, programmers and content producers. The ability to design simulations and virtual environments that immersed students in 'real-world' issues became widely available at relatively low cost. For example, the award-winning CD-ROM *Exploring the Nardoo*—developed in 1996 at the University of Wollongong - contained the necessary scientific information about pollutants, chemicals, natural processes, biology and animal species for students to engage with the complex ecology of a river system and design solutions for better management of water resources (Bennet, 2007).

Tablet applications represent the next stage in this unfolding development of rich multimedia for science education, where devices such as iPads, other tablets and smartphones are now ubiquitous in the hands of learners, and the costs of design and production have dropped even further. The app was initially prototyped as an iOS app that entailed sophisticated coding, but then was developed into production using the App Builder components of Adobe Digital Publishing Suite (Adobe Systems Incorporated, San Jose, CA, USA). These tools are user-friendlier than platform specific coding, requiring fewer technical skills to execute; therefore, the process of app development is now relatively simple and does not necessarily require programming expertise or the large team of specialist developers needed for earlier multimedia development projects. In fact, the app was designed and developed predominantly by a group of post-graduate and undergraduate students from different disciplines across science, art, and design. Because the app was designed partly by students, it is instinctively tailored to the aesthetics and educational level of first year university students. However, the app is appropriate for a much wider audience including final year high school students, post-graduate university students, and the general public with an interest in global environmental change and the drivers of climate change.

This interdisciplinary approach responds to emerging realisations that science needs to work in partnership with other areas of Universities, such as the creative departments, biological and social sciences, to ensure that students and citizens are empowered to learn about the scientific dimensions of climate change, and design tools and applications that provide creative engagement with facts and data. As Nisbet, Hixon, Moore and Nelson (2010) point out, environmental scientists need to work with creative artists to accurately communicate about science, with the aid of digital media, in imaginative, compelling, and novel ways. This is not to say that the ease of development and widespread accessibility of multimedia mobile applications automatically translates into enhanced understanding and the kinds of action required to bring about deep transformation in the cultural and economic processes at the root of ecological problems. The authors are sensitive to critics such as Bowers (2014) who argue that the dominant ideology of 'progress' that informs scientific and technological thinking leads to indifference in understanding how to make the transition to an ecologically informed form of consciousness. The contradiction here is that the market system and new digital technologies contribute to changing consciousness in ways that are even less ecologically sustainable. Nevertheless, the approach to developing the app takes the position that it is better to creatively use the potentials and affordances of new digital media to educate for informed scientific literacy, rather than to ignore the transformative potential of mobile applications that clearly engage and stimulate learning for students.

One major issue in provision of learning applications on mobile devices is the 'digital divide' where, for reasons of equity and fairness, it is important to ensure that all students have access to the digital resource. The digital divide is not a new issue in technology-enabled learning, but as Zhang et.al. (2015) note, research shows a clear increase in information needs for mobile education since 2008, both globally and in the United States. Further, the research indicates a positive correlation between the Web information needs for mobile education and the achievement gap, suggesting an emerging trend of digital divide in mobile technology.

The app addresses this issue in three ways. Firstly, it is free to download under a Creative Commons license, thus removing any financial barrier to students for obtaining it. Secondly, the app is designed on BYOD (bring your own device) principles. The affordances of Adobe DPS as the design tool enable the app to be cross-platform, and viewable on any device. Thirdly, for the very small minority of students who may not own a smartphone or tablet, the app is also available to desktop computers on the university network. The latter affordance also enables it to be used a teaching tool by lecturers in classrooms who can simply display the app along with any other digital media on the lectern computer. From experience, the authors have made use of the app as a teaching tool at tertiary level in New Zealand, over 90% of students had access to a mobile device: either a smart phone or a tablet. The remaining students did not find it difficult to access the app via a desktop or laptop computer. In fact, some students preferred to access the app via a computer, as they preferred to keep their private activities, for which they predominantly used their smartphones, separate from their studies.

SOLUTIONS AND RECOMMENDATIONS

The app is a teaching support tool that is designed to clarify the interconnectedness of the global carbon and water cycles and to help students in fostering system thinking skills. The app uses clean illustration, concise explanations of the process and features and interactive animation to describe how the cycles are connected through the stomata, bringing together key scientific concepts that are often taught in isolation. The impetus behind the development was to provide an innovative medium (in an era of mobile devices and "there's and app for that" mentality) for translating complex ecological processes in addition to traditional teaching resources, such as lecture slides and textbooks. The following examples of how the app could be used in a lecture setting illustrate a collaborative teaching approach, where students can use the interactivity of the app to improve their understanding of the role of stomata in the carbon and water cycles, and deepen their understanding of the interconnectedness of global cycles and human activities. The authors focus these learning pathways on addressing students' gaps in understanding, and encouraging independent learning that is supported by a lecturer.

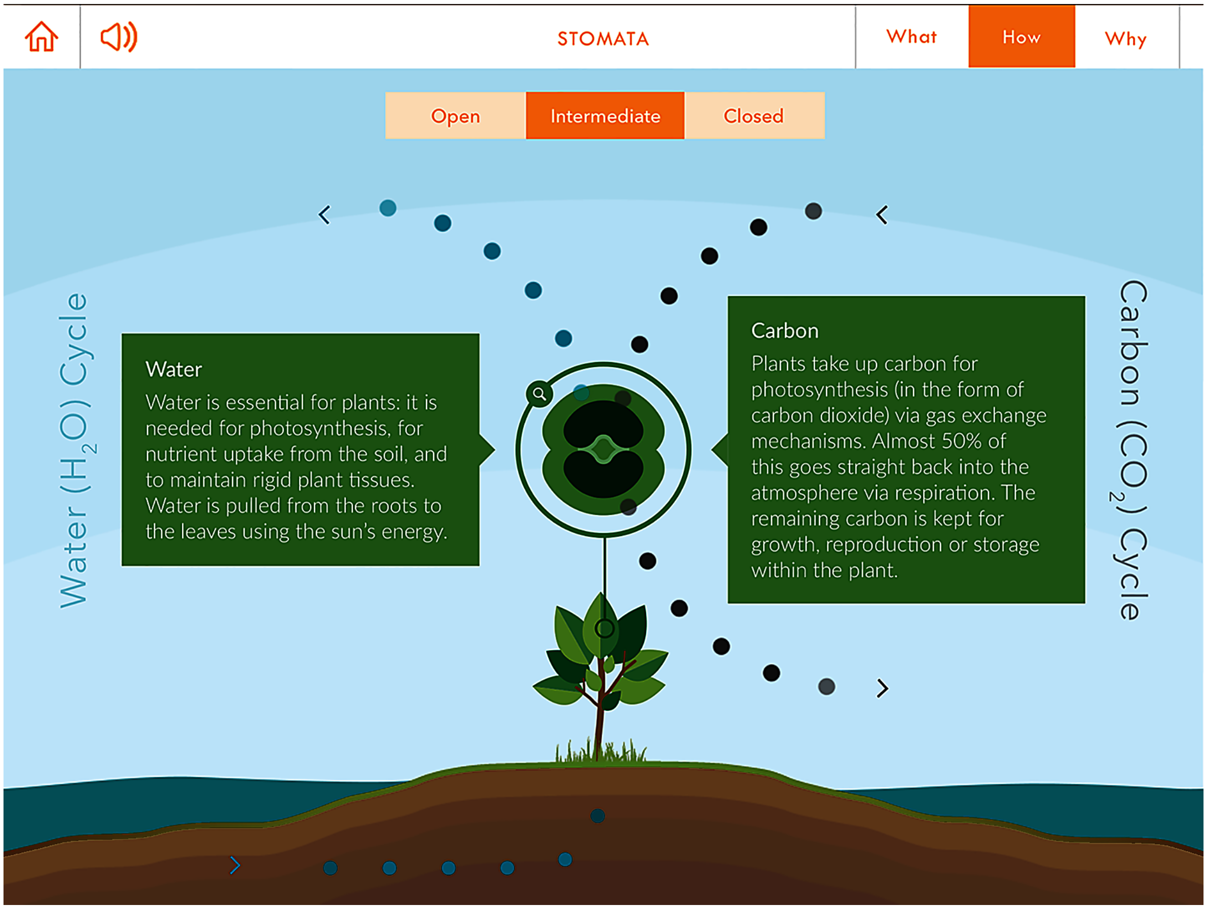
The first example of a possible learning pathway using the app investigates the physiological function of stomata, and how environmental influences affect the transport of water and carbon between the terrestrial and atmospheric pools. The second example explores the global carbon and water cycles. The third example explores the climate feedbacks that are influenced by human activities. The authors emphasize that the app is designed in a way that allows flexible, interactive learning, and therefore the pathways presented here are examples only, thus the app allows for institute-specific learning outcomes to be addressed and new learning approaches to be explored.

Learning Pathway Example 1: What Are Stomata and How Do They Work?

The content on the *What are stomata?* page describes how varying environmental conditions drive stomatal opening and closing, and why water is necessary for photosynthesis (McKown, Cochard, & Sack, 2010). Here, students can control how much water and carbon enters the plant by selecting various levels of stomatal opening. This interactivity allows students to see how changes in stomatal opening affect the physiological functioning of the plant, thus how these changes can affect the global carbon and water cycles, providing a platform for students to develop system thinking skills.

On the *How* tab of the *What are Stomata?* page, there is an explanation of the influence of carbon and water on the physiological function of the stomata is given (Figure 1). Ambient CO_2 concentrations influence stomatal opening and closing. The lecturer can point out that, because of these dependencies, the rates of photosynthesis have, albeit slowly, fluctuated in response to atmospheric CO_2 concentrations

Figure 1. Screenshot of the How page in the What Are Stomata? section of the Global Change app



over the millennia (Beerling & Franks, 2010). The *How* tab shows animated and interactive diagrams to describe how the delivery of soil water through the vascular system of the plant, and the simultaneous exchange of CO_2 and water vapour from the atmosphere through the stomata link the carbon and water cycles inside the microscopic architecture of leaves (Ferguson & Veizer, 2007; Beerling & Franks, 2010).

Plants face a wicked dilemma, where if they open stomata, CO_2 can enter the plant, but at the same time they lose water through transpiration. If stomata close, they save water, but not much CO_2 can enter (they get 'hungry'). The app's animation and interactivity show how in a highly choreographed dance, the stomata respond to variable water and carbon availability due to stochastic environmental conditions in order to maximise CO_2 assimilation for photosynthesis, while minimising water loss through transpiration (Ferguson & Veizer, 2007). The external links embedded in the *What are Stomata?* pages, and throughout the app, can be used to direct students to additional information sources. The lecturer could explain in detail what CO_2-physiological forcing is and how it leads to stomatal closure (Cao, Bala, Caldeira, Nemani, & Ban-Weiss, 2010), reducing the uptake of carbon by terrestrial vegetation using these links. CO_2-physiological forcing is the response of stomata to elevated CO_2 concentrations in the atmosphere (Cao et al., 2010). The stomatal pores open less widely, reducing canopy transpiration, which in turn leads to a reduction in evapotranspiration (soil evaporation + canopy evaporation

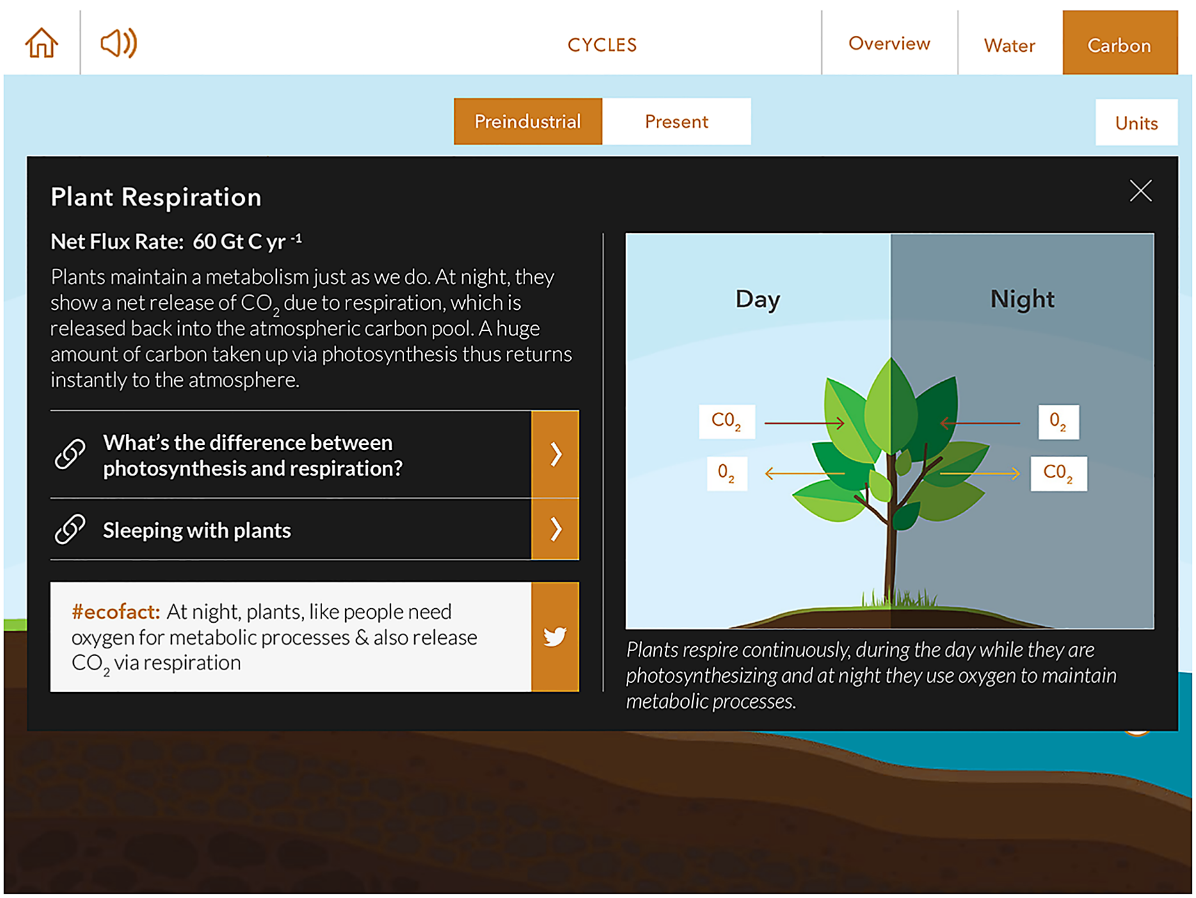
+ canopy transpiration), which are further described in the cycles page of the app. Decreased stomatal conductance reduces transpiration rates, thereby decreasing the cooling effect and reinforcing surface air warming, which provides the cognitive link for students to begin to think about the positive feedbacks of climate change (Bonan, 2008). Here, students could be guided to think about how this might affect the atmospheric water pool (e.g. warm air has a greater water holding capacity than cold air).

The *Why* page of the app describes the main environmental drivers of stomatal regulation. For example, how the assimilation of CO_2 declines at both low temperatures and at high temperatures (Farquhar & Sharkey, 1982). In this way, students are introduced to how the influence of human activities affects stomatal functioning and the feedbacks initiated by these first-order responses. Students can be encouraged to think and discuss how the environmental factors that influence stomatal functioning may be reinforced or act antagonistically.

Learning Pathway Example 2: The Global Carbon and Water Cycles

The app provides and overview of the global carbon and water cycles, introducing the pools and fluxes in the pre-industrial and in the Anthropocene (present) context. The design of the *Cycles* page is done

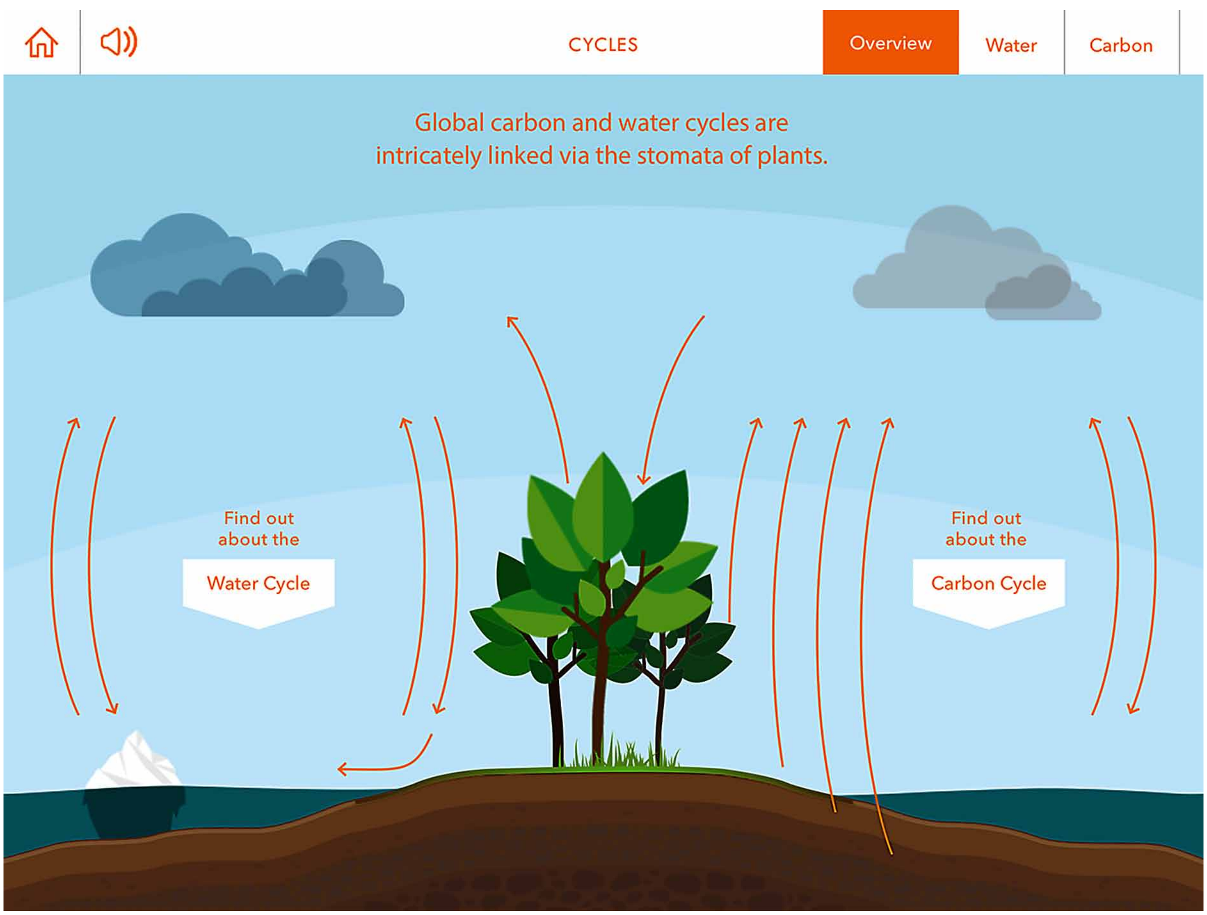
Figure 2. Screenshot of the overview of the carbon and water cycles in the Global Change app



in a way that illustrates the key concepts of each component, how the pools are linked by fluxes through the system and processes in a way that can be easily understood by students (Figure 2). By linking the pools and fluxes in this way, students can trace carbon and water between different system components, providing conceptual connections for how human activities affect different components of the cycles. Clearly distinguishing between matter fluxes vs. pools is critical, as misunderstandings that high fluxes lead to high pools exist even among scientists (Asshoff, Riedl, & Leuzinger, 2010; Leuzinger & Hättenschwiler, 2013). Further, by using the stomata as a link between the water and carbon cycles, the app addresses the misleading contemporary approach of viewing the carbon and water cycles as separate processes. This linkage will not only give students a more authentic understanding of these biogeochemical processes, but it will also allow an integration of the impacts of global change by including predictions and feedbacks illustrated in the *Climate Change Connections* section of the app (described below).

The global carbon cycle is the interconnection of four main pools by the exchange (flux) of carbon through physical, chemical, and biological processes (Holmén, 2000). These fluxes connect the atmosphere, the hydrosphere (oceans and surface waters), the biosphere (vegetation and soil), and the geosphere (sedimentary rocks, caltrates, deep marine sediments) carbon pools (Holmén, 2000). The app describes the link between the soil carbon pool and terrestrial vegetation, which is dominated by

Figure 3. Screenshot of plant respiration in the pre-industrial carbon cycle of the Global Change app



symbiotic associations of mycorrhizae fungi with 80% of terrestrial plant species (Figure 3) (Cheng et al., 2012). This is important because, as said above, at an ecosystem level, students often fail to grasp the importance of the key processes respiration and photosynthesis for explaining carbon fluxes of the global carbon cycle. In this context Ebert-May et al. (2003) investigated US-students' understanding of the carbon cycle in introductory biology courses for science majors. In different problem-based tasks concerning the carbon cycle, students were asked to explain processes and pathways and organisms involved when tracing the path of a carbon atom through the system. For example, students were asked to describe how a C-atom in a body of a dead person ends up in a different organism. The results clearly showed that not all students had internalized that decomposers produce CO_2 (soil respiration, heterotrophic respiration). Instead, they thought that plants acquire carbon from the soil rather than from the air through leaves during photosynthesis - a persistent and well described conception of students, found in all age groups (e.g. Driver et al., 1984).

The processes of respiration, photosynthesis, decomposition and soil respiration are explicitly addressed on a terrestrial ecosystem level in the carbon and water cycles section of the app using figures, text-tables and problem tasks (e.g. "Can sleeping in a room full of plants be dangerous?"; In the *Plant Respiration* node, the content concisely explains that plants photosynthesize during the day (when there is light) and respire continuously. Photosynthesis drives the flux of carbon between the atmosphere and terrestrial biomes at a rate of ~120 Pg (petagrams) C yr^{-1}, termed gross primary production (GPP). The lecturer could explain in more detail the process of photosynthesis and respiration using the app as a guide. Then it could be emphasized to the students, that approximately half (~60 Pg C) of that carbon is released almost immediately back into the atmosphere through plant respiration, and the remaining carbon (~60 Pg C) or net primary production (NPP) is (temporarily) stored in living biomass (Ajani et al., 2013). In this way, students are using a system thinking approach because they see that components of a system (atmosphere and terrestrial biome) are linked via respiration and photosynthesis and thus improve their understanding of the cyclic nature of biogeochemical processes (e.g. Sibley et al., 1997).

The app can be used to identify the differences between the types of respiration (e.g. heterotrophic and autotrophic respiration) with the *Terrestrial Respiration* node. Here, the content and interactivity of the app illustrates that when plant biomass senesces, carbon that is stored in NPP is shunted to the soil pool by plant and root senescence and turnover, and the appropriation of photosynthates by arbuscular mycorrhizal fungi (AMF) (Price et al., 2012). Carbon that leaves the terrestrial biosphere through respiration by soil microorganisms and natural disturbance events, such as fires, returns the equivalent of NPP back into the atmospheric carbon pool, with net vegetation storage of ~3.3 Pg C ha^{-1} yr^{-1} (Bonan, 2008; Ajani et al., 2013). This connection represents an important cognitive link between respiration, the atmospheric flux, decomposition, and the soil sinks of the global carbon and water cycles (Verbruggen et al., 2013). Students can further explore this concept through the link to additional resources: "*What is the difference between photosynthesis and respiration?*" This learning pathway encourages students to think about the process of respiration and photosynthesis in a way that highlights the connection of the stomata to the global carbon cycle, and about the timescales involved in carbon cycling through the biosphere. Lecturers may suggest that students think about the temporal scales involved in the global carbon cycle and why some parts (e.g. geocarbon, such as rocks in the lithosphere) are excluded from the active carbon cycle when thinking about climate change models), again an example of system thinking!

In the *Present* carbon cycle students can investigate which pools and fluxes have been altered because of human activities. A lesson could focus on the *Atmospheric Pool, Oceanic Pool* and the fluxes between them. For example, of the 192 $\pm$ 29 Pg C of anthropogenic CO_2 that has accumulated in the biosphere, approximately two thirds (118 ± 19 Pg C; Sabine et al., 2004) has been absorbed by the oceans. Students can be encouraged to investigate how the carbon is transferred from the atmospheric pool to the oceanic carbon pool, and what are the implications of this for animals in the oceans (e.g. ocean acidification and calcifying organisms).

The app connects the concepts of respiration, the carbon pools and water cycles and emphasizes that the geographic location and condition of forests plays a crucial role in the cycling and storage of carbon, which are also tightly coupled with the water cycle through rainfall patterns. Thus, students can begin to make conceptual links between human activities and impact on vegetation, and the carbon and water cycles (e.g. what is the distribution of deforestation and where are areas of high productivity?), which are described in more detail below. Here, as with other content, the app allows the flexibility for students to explore the process of decomposition through the content and external links to improve their understanding, either in the classroom, for homework assignments or general interest. The app can also be used to address specific students´ conceptions about the water cycle. As in the carbon cycle, the app describes the main fluxes and pools of the water cycle in the pre-industrial and the Anthropocene context, providing students with explicit ways of viewing the changes to the water cycle from human activities. In a study with Israeli Junior High students, Ben-zvi-Assarf and Orion (2005) describe the perception and understanding of the water cycle for students as being naïve and incomplete. The water cycle was in general reduced to atmospheric components (evaporation, condensation, and rainfall). More precisely, 70% out of 177 students ignored the groundwater component of the water cycle. Students who mentioned the groundwater component described it as static and isolated from the other fluxes and pools of the cycle.

Some of these conceptions may be due to only a very small percentage of high school and university students being exposed to all of the components of these global cycles. For example, in Isreal, the water cycle is already taught in elementary school (4th grade), but most of the programs do it in a naïve way that focus only on the atmospheric cycle. Similarly, the junior high (7th – 9th) programs that deal with the carbon cycle usually do it in a naïve approach that focuses mainly on the biosphere-atmosphere cycle (N. Orion, personal communication, May 14, 2015). The app, in contrast describes the pools and fluxes of the water cycle in a way that illustrates the connections between each main component and connects them through visual cues and content, thus addressing the above misunderstandings using a system thinking approach. For example, the app content describes the dependency of terrestrial vegetation on water, which is somewhat intuitive. Plant growth is generally higher in areas of high water abundance (where there are groundwater reservoirs; Ferguson & Veizer, 2007). Connecting the stomata to the global water cycle is emphasized in the app because of the importance of terrestrial transpiration, which represents the largest water flux, responsible for the recycling of 80-90% of continental surface waters (Jasechko, Sharp, Gibson, Birks, Yi, & Fawcett, 2013). This means that an astonishing ~62,000 km^3 of water passes through stomata, a flux equivalent to 30% of precipitation falling on the earth's land surface every year (Beerling & Franks, 2010; Jasechko et al., 2013). Described in this way, the app content and design connects the importance of the role of stomata in the water cycle and the large fluxes of water between the soil, groundwater and atmospheric water pools. Understanding the magnitude of transpiration and carbon fluxes of terrestrial vegetation, and the links to other fluxes in the cycles provides students with a greater capacity to understand the water cycle and how human activities can influence the world's climate.

Here, the app fills a gap by focussing on content knowledge and thus on explaining scientific phenomena. Further, the app can serve as a starting point to address other issues beyond content knowledge and to convey procedural and epistemic knowledge (or in general the "nature of science", Lederman, 2007) to explain to students how the science of global biogeochemical cycles work (e.g. how carbon fluxes are measured). Thus, the applicability of the app is not limited to content knowledge. For example, based on the knowledge of the water- and carbon cycle it is possible to start a debate about sustainable development and the human impact on the carbon cycle, leading to the illustration of the interdependence of ecological (water- and carbon-cycle), economical (drinking water supply) and social dimensions (climate change impacts on society, e.g. drought). Here, the connection between personal energy resource use and climate change (e.g. climate change and ecological footprint (Cordero et al., (2008)) can be discussed.

Learning Pathway Example 3: Exploring Climate Change Connections

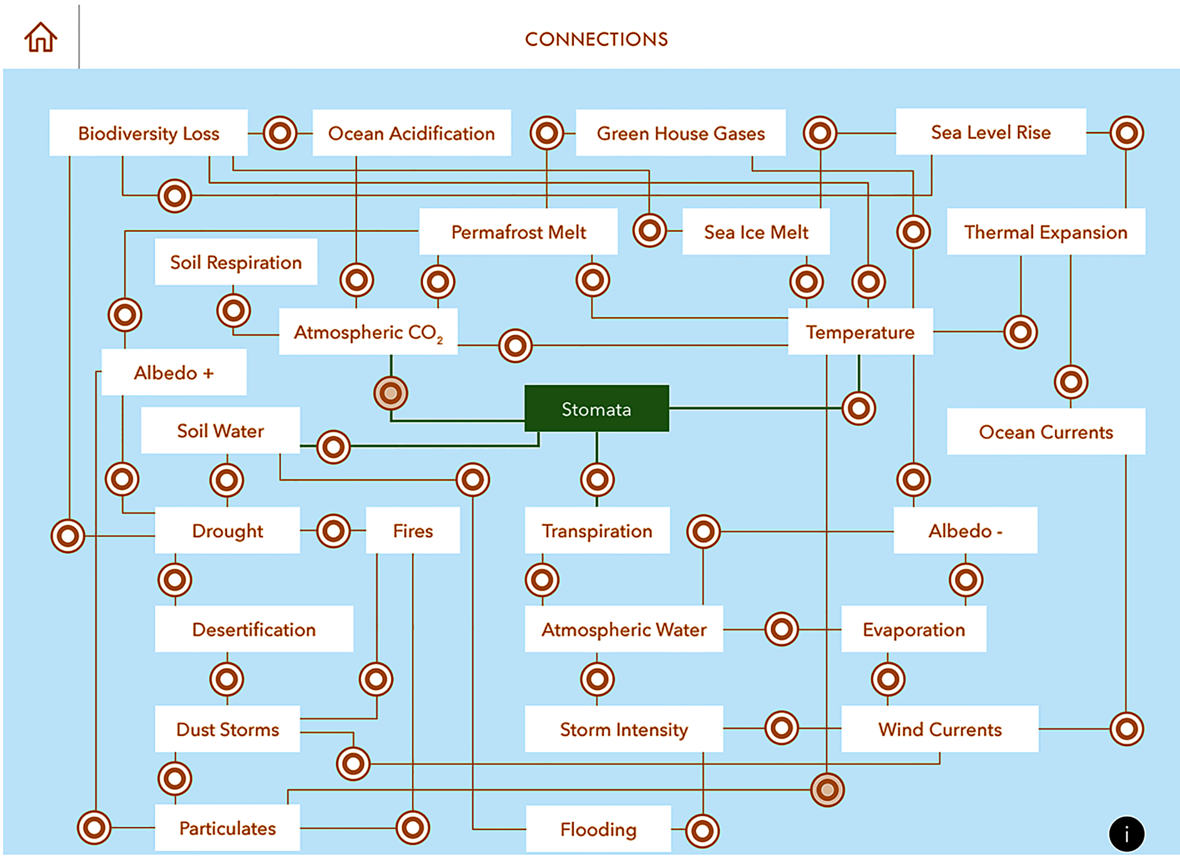
The final concept of the app is the *Climate Change Connections* page. This section of the app explores how human impacts, such as CO_2-induced increases in radiative forcing, land-use change, and fossil fuel emissions influence the global carbon and water cycles, particularly through changes in physiological responses of plants. In a survey of American adults (August 15-25, 2014), 50% of respondents were not convinced that human activities were mainly responsible for climate change (Funk, Rainie, Smith, Olmstead, Duggan, & Page, 2015). This disconnect between widely accepted climate science and public opinion stems from a complex set of social and political drivers, beyond the scope of this chapter. However, educators often describe inaccurate student conceptions of climate change related issues (Cordero, Todd, & Abellera, 2007). For example, students discussed stratospheric ozone depletion as a driver for the enhanced greenhouse effect, when quizzed about global warming (Jefferies, Stanisstreet, & Boyes, 2001; Cordero et al., 2007). However, the two are entirely unrelated.

Students often think in one-way causal ways, although there are different or more complex ways including different feedback loops (Sweeney & Sterman, 2007). For example, burning of fossil fuel does not only lead to rising atmospheric CO_2 concentrations, it also impacts oceans, as CO_2 dissolves and carbonic acid is formed, leading to a higher acidity, which has negative impacts on marine fauna. Ben-zvi-Assarf and Orion (2005) revealed that a lack of system thinking by students was responsible for the perception of the global water cycle, that underground water is not associated with human activity and thus water quality. The students showed a very fragmented knowledge about the water cycle and had difficulties to understand the transformation of matter in the earth reservoirs. They contributed this difficulty partly to the way this topic is approached at school (or in teaching materials).

System thinking is addressed in different ways using the app. Students can work out the two cycles under preindustrial conditions and under present conditions. For example they see that rising temperatures, caused by increasing CO_2 concentrations, lead to higher evaporation rates, which can alter worldwide precipitation rates. Finally, they can use the flowchart (network) in the *Climate Change Connections* page to gain an understanding about global change feedbacks (Figure 4). Here, up-to-date climate change science is presented in a network, so that students can visually trace how the effects of human activities manifest in the natural world. Each ‘node’ within the network represents one of the key climate change effects. The content briefly explains what the impact is and how it has been enhanced or dampened by human activities, providing links and additional resources for students to explore climate change effects. In addition, between each climate change node the app has integrated interactive popups, which briefly explain how the climate change nodes are connected to each other.

Using the educational apps, such as *Global Change,* to teach about the effects of climate change feedbacks allows learning pathways in the classroom to be dynamic; where students can follow their own interests independently. For example, if the class starts on the *Temperature* node, students can learn about CO_2-radiative forcing (the increase in mean surface temperature from elevated greenhouse gases

Figure 4. Screenshot of the Climate Change Connections page in the Global Change app

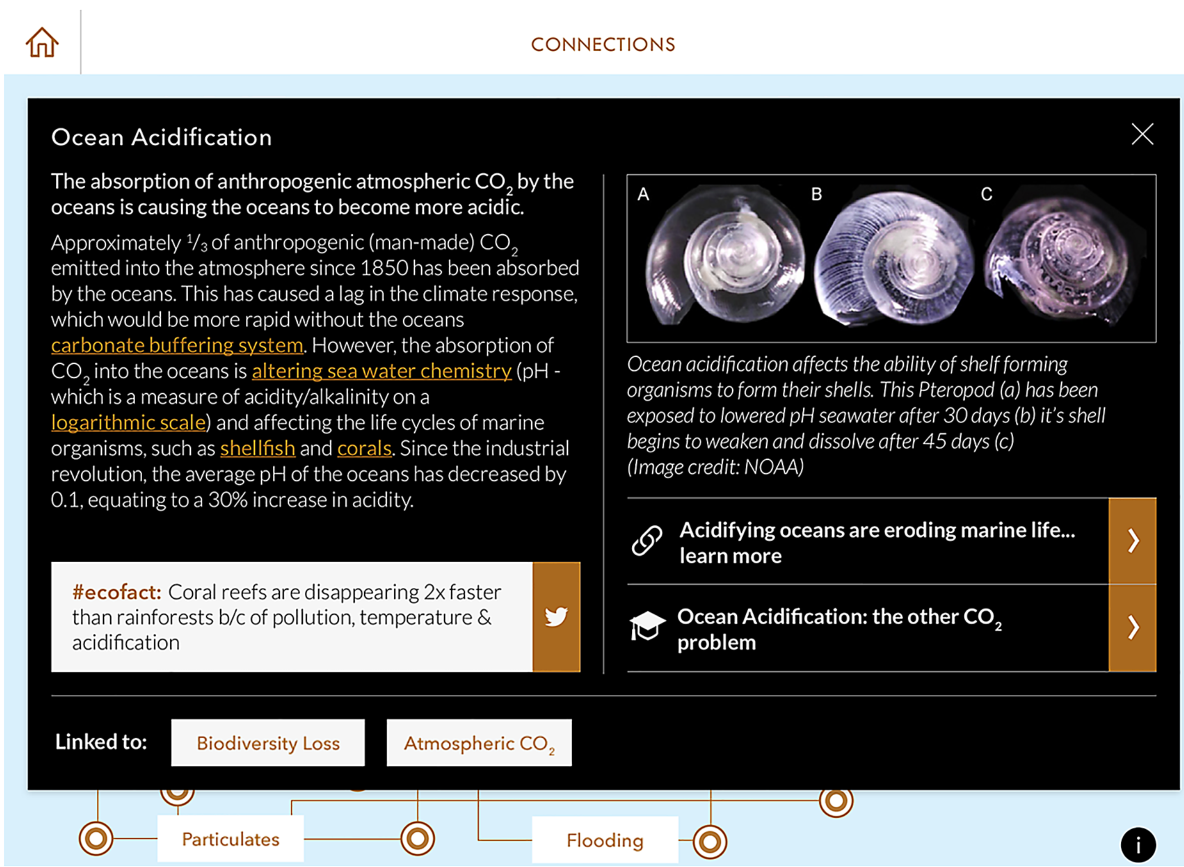


in the atmosphere), which means that atmospheric water vapour distributions are altered because in higher temperatures evaporation rates are increased (Huntington, 2006; Cao et al., 2010). Students then have the independence to explore the climate change feedbacks that are directly, or indirectly related to temperature. A student may be interested in the *Land use change* node, and learn about how the extensive blocks of near pristine forest have been rapidly converted to farmland, cropland, pasture, and urban areas with increasing rates of habitat and biodiversity loss (Laurance et al., 2006; Gardner et al., 2009).

If the lecturer chose to provide more specific guidance to the students, while retaining independent learning practices, the students could be asked to think about and discuss the reasons behind land-use change (e.g. human population growth, consumptive practices), and the spatial distribution of land-use (e.g. population density, arable land, resource distribution). For example, in addition to direct influences from land clearance, land use change affects rainfall patterns. In the last century, precipitation over land has increased approximately 2%, although patterns are regionally variable (Huntington, 2006). Here, the students may be encouraged to think about how these events might exert feedbacks on plant responses locally and regionally, by either inundating vegetation, or inflicting drought stress respectively, which both affect transpiration rates and further perpetuate climate feedbacks (Bonan, 2008). Alternatively, in a group discussion format, students could be questioned about what happens in areas of increased precipitation? The lecturer can guide the students to think about surface runoff, which redistributes soil nutrients away from terrestrial vegetation, aggravating nutrient limitation for plants and affecting soil structure (Huntington, 2006). Further exploration could include questioning how changes to the atmospheric water vapour distribution might initiate interacting and non-linear feedback loops, which further affect surface temperatures, CO_2 concentrations and intensification of the water cycle (Field, Jackson, & Mooney, 1995; Cao et al., 2010).

While the app's purpose is to provide a broad overview of complex global scale biogeochemical process and has been simplified considerably, the links to external sources of information mean the app can be used for a range of skill levels, and course requirements. For example, the app could be used in a specialist paper, such as an oceanography, or marine chemistry to discuss ocean acidification. The *Ocean Acidification* node describes briefly how the oceanic carbon cycle is driven by a continuous series of biogeochemical reactions (Doney, Balch, Fabry & Feely 2009; Orr et al., 2009; Figure 5). Students can learn the complexities of the carbonate buffer system, which absorbs atmospheric CO_2 at the air-sea interface. In the text boxes, embedded links take the user to a more comprehensive description of pH, so students can further explore the chemistry of the oceans and the processes that affect the cycling of carbon through space and time. Because of the increasing rate of CO_2 emissions from human activities, such as land-use change and energy production, the buffering capacity of the world's oceans is being

Figure 5. Screenshot of the climate change node Ocean Acidification in the Climate Change Connections page of the Global Change app



compromised, leading to ocean acidification (Orr et al., 2009). While the content in the node is brief, the links to additional resources explain that the concentration of anthropogenic CO_2 in the surface waters is highly variable, determined by surface water chemistry, currents and temperature (Sabine et al., 2004); whereby the levels of content within each node allow students to explore the issue as little, or as much as required to meet their learning outcomes and their own curiosity.

FUTURE RESEARCH DIRECTIONS

The tight coupling of carbon and water through stomata provides an ideal focal point for teaching the global carbon and water cycles to students. This app, *Global Change,* is based on the holistic earth systems approach and deals with these cycles in the context of the interrelationships among all the earth systems geosphere-atmosphere-biosphere using a system thinking approach. Understanding of the structure of the pools and fluxes of the carbon and water cycles is of critical importance for understanding how human activities influence global change. As identified above, the app is an example of a teaching tool that is flexible and interactive, which capitalizes on mobile devices that are ubiquitous in the hands of learners. Further, the flexibility of system thinking educational apps is not limited to science, thus the *Global Change* app is suitable for a range of non-ecological-science learning environments, such as health sciences, business studies, engineering and many others where it is important for learners to have an understanding of the interconnectedness of the natural world, and how human activities can influence natural processes.

The authors suggest that future research directions are to develop an array of educational apps that can be used as teaching support tools. The development of such apps shouldn't be restricted to higher education, but embrace mobile devices as tools for learning at every level of the education system internationally. A simplified version of the app would assist in developing a system thinking approach in students from a younger age, potentially improving their ability to grasp complex ecological processes in more demanding higher-education environments. Additional developments in educational apps, such as *Global Change* could include the capacity to evaluate student progress from within the app, where evaluation results could be sent directly to the lecturer for assessment, and where the student gets immediate feedback. While, educational apps that provide a system thinking approach for teaching complex processes, not only ecological and earth systems, could provide valuable teaching support tools for educators worldwide, much research is still needed to evaluate the effectiveness of using mobile devices in the classroom. This research is imperative so that such educational apps, and the use of mobile devices in the classroom can maximise students' learning but also contribute to improving design and usability for both educators and students.

CONCLUSION

Higher education plays an important role in promoting a comprehensive understanding of the scientific concepts of the global carbon and water cycles, and how human activities affect the natural world (Cordero et al., 2007). With this understanding, students can initiate and participate in topical conversations about climate change and contribute to finding solutions to these issues. In this chapter, the authors have presented the *Global Change* app, a mobile device based teaching tool that illustrates the leaf level processes of photosynthesis, respiration, and transpiration through the stomata of plants, their connection to the global carbon and water cycles and their response to human activities. The app conception through to development was initiated and built primarily by tertiary students, in this way, the app is designed so that it directly relates to how tech savvy students learn and interact with their mobile devices.

This chapter illustrated that there is a variety of student conceptions about the global carbon and water cycles and how human activities are impacting on them. Many of the conceptions arise from everyday experience, whereas others are developed through teaching. Reasons for some alternative conceptions might be found in poorly interconnected curricula structures. Although, the authors did not conduct a detailed curricula study on this topic, there are some hints that in many cases water and carbon cycles are taught independently from each other and in different school grades or subjects. This implies that the level on which the cycles are taught may lead to alternative conceptions that do not match the scientific evidence. Here the *Global Change* app fills a gap, because it encompasses the water cycle and carbon cycle as well as the socially important topic of climate change on a content knowledge level within one education app, which is freely available for all mobile devices.

In the context of system thinking, the *Global Change* app allows a structured teaching procedure because water- and carbon cycle can be first discussed under pre-industrial conditions and second under present conditions. Embedded in the content are graphs from peer-reviewed scientific literature, the International Panel on Climate Change (IPCC) and other scientifically robust sources enhance the text content and provide learners with visual tools, and links to more information if they choose to explore specific concepts further. Further, the climate change connections are illustrated as a network, linking to the central component, the stomata. In this way, students can see how global scale processes are linked to local climate change effects, and to leaf level processes. Finally, the in-built twitter functionality, with the #ecofact tag means users can share their new knowledge with friends, family and peers to create a social conversation around climate change issues. Such discussions facilitate the continued learning and exploration of the natural world and climate change issues beyond the walls of academic institutes, contributing to a more informed and engaged society. Educational apps, such as *Global Change,* available on a range of mobile devices are the ideal platform for engaging tech-savvy students for studies in ecology, the environment and climate change by the way that it integrates complex scientific concepts, design and animation in a captivating and educational way.

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KEY TERMS AND DEFINITIONS

Application: Software designed for smart devices (e.g. iPads, iPhones, android tablets and phones) that allow the user to perform activities, functions and/or tasks in an interactive way.

Biosphere: The area or zone on the earth where biological organisms exist, which includes biodiversity; the total diversity of all living things within an ecosystem at various spatial scales, biomass; the total mass of all living organisms in a given area or volume, and biome; the geographic region that contains distinctive community of living organisms and climatic features.

Carbon Cycle: The term used to describe the flow of carbon (in various forms e.g. carbon dioxide) through the atmosphere, oceans, terrestrial biosphere and lithosphere.

Fluxes: The movement of water or carbon between the earth's carbon and water pools (e.g. oceans, atmosphere, and terrestrial vegetation) via chemical and biological processes.

Global Change: Planetary scale changes to atmospheric circulation, ocean circulation, climate, the carbon cycle, the nitrogen cycle, the water cycle and other cycles, sea ice changes, sea-level changes, food-web alterations, biological diversity loss and change, pollution, ecosystem health, changes to fish stocks and more.

Stomata: Microscopic pores on the surface of the leaves and stems of plants through which gases (carbon dioxide, oxygen and water vapour) are exchanged.

System Thinking: A learning approach that focuses on the understanding the components of a system and how they interrelate to each other.

Water Cycle: The cycling of water through the atmosphere, oceans, lakes, rivers, ice, aquifers, and soil. The cycle is made up of pools and connections (fluxes).