



**Connecting Photosynthesis and Cellular Respiration: Pre-Service
Teachers' Conceptions**

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Connecting Photosynthesis and Cellular Respiration:
Pre-Service Teachers' Conceptions

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Abstract

The biological processes of photosynthesis and plant cellular respiration include multiple biochemical steps, occur simultaneously within plant cells, and share common molecular components. Yet, learners often compartmentalize functions and specialization of cell organelles relevant to these two processes, without considering the interconnections as well as the significance of the plant as an independent biological system functioning as a nested component within local and global ecosystems. Understanding connections among biological systems at macro and micro levels is important to biological literacy. This study examined preservice elementary teachers' conceptions of photosynthesis and plant cellular respiration, with attention to interconnections and systems. Participants were limited in their understanding of the processes impacting multiple ecological levels, and they held inadequate representations of interconnections between the processes. Participants' views were laden with sociological and egocentric components. They often compared plant functions with analogous human functions. Most participants viewed plants as dependent on humans while having societal use. Justifications for views included nominal knowledge of the processes; experiential authoritarian reasoning; and anthropomorphism. We discuss instructional implications in light of the findings.

Key words: [Undergraduate; Biology conceptions; Systems; Pre-service teachers; Photosynthesis; Cellular Respiration]

Years ago, a college biology student in one of my classes pointed to the mitochondria on a plastic model of a typical plant cell and explained that plant cells do not need mitochondria because “they get their energy directly from the sun.” The student failed to see the need for plant cellular respiration, not recognizing that both photosynthesis and cellular respiration are energy reactions within a biological system. This failure suggested a conception of biological processes that ignores the concept of systems and the component levels. Photosynthesis and plant cellular respiration include multiple biochemical steps and occur simultaneously within plants. Understanding these processes can be challenging. Students who compartmentalize function and specialization of organelles at the cellular level may not consider interconnections between the processes, and may miss the significance of the plant as an independent biological system functioning within a local ecosystem, as well as within a global ecosystem. *Systems* is a unifying theme across science disciplines (Rutherford & Ahlgren, 1990). Systems awareness is advocated for elementary science education as early as kindergarten (AAAS, 1993). Thus, there is a need to explore learners’ conceptions of connections of biological processes within and among organizational systems. This study explores preservice elementary teachers’ conceptions of photosynthesis and cellular respiration, interconnections between the processes, and functions within multiple systems.

Theoretical Framework and Related Literature

In *A New Scientific Understanding of Living Systems: The Web of Life*, Capra (1996) provides an historical view of the classical tension between viewing living organisms as integrated wholes, or as subunits. He suggests scientists Descartes and Galileo advanced a philosophy that living organisms, although very complicated, could be understood in terms of their physical and chemical components. It wasn’t until the early twentieth century that a new idea regarding life’s organization arose (Capra, 1996). This recent view of the living world

incorporates a level of organization that goes beyond physical and chemical components, promoting the idea of systems. To understand a living organism as a system, the inherent chemical and physical elements are acknowledged to organize across multiple levels within the organism. Each system forms a whole with respect to its component parts, such as component parts of cellular metabolism. At the same time, each is part of a larger system, such as the whole cell, organ, or organism. In this respect, biological systems encompass multiple ecological levels and are “nested.”

One of the fundamentals of biology is that sense can be made of the complexity of the biosphere by viewing it as a set of interrelated systems that can range in size from the subcellular to the ecosystems level. We can trace matter and energy within these systems to understand them individually and between these systems to understand their interdependence. (p. 324, Wilson, Anderson, Heidemann, Merrill, Merritt, Richmond, Sibley, & Parker, 2006)

The Plant as a System

Plants bring together raw materials into cellular compartments that comprise the organism. The organism interacts within the ecosystem and influences the global environment. The plant is a system. Moreover, the plant is a component of nested systems. Figure 1 schematically illustrates the plant as a system within the biosphere. Each circle represents a “multiple ecological level” as described by Waheed & Lucas (1992) while the entire figure represents the plant within the biosphere. Recognizing the significant input of oxygen into the global system, we added the additional level (global) that extends the work of Waheed and Lucas. Focusing exclusively on actions or components of one level does not readily convey interconnections within the levels or interactions between levels. A systems view would

recognize the interdependence of processes within and between systems at multiple ecological levels (Wilson et al., 2006).

-----[Insert Figure 1 here]-----

Each ecological level has its own properties. For example, green pigmentation alone can not be observed below the cellular level, but when combined with light, it becomes chlorophyll, and the green property becomes visible. Such properties are termed emergent, because they exist only at higher levels of organization. Emergent interactions within and between ecological levels can be holistically considered as a “nested” system as each level is a subsystem (Figure 1). Such a systems view of plants may be challenging for learners, as they tend to compartmentalize the interactions within complex dynamic processes (Marmaroti & Galanopoulou, 2006) knowing the “when” and “where” but not knowing the exact roles of the components, the chemical changes, origins, or destinies (Wilson et al., 2006). Because photosynthesis and plant cellular respiration occur in multiple ecological levels and within multiple complex systems, the learner must consider that actions on multiple ecological levels occur simultaneously and continuously, and not as “step-by-step processes” (Chi, 2001).

Photosynthesis and Cellular Respiration as Interconnected Processes

Photosynthesis and plant cellular respiration are “complex dynamic processes” because of their abstractness and multiple ecological levels (Chi, 2001). These processes are “nested systems” in that the plant is a biological system in its own entity, and is a component within the larger global ecosystem. Photosynthesis and cellular respiration are interconnected as the two processes combine to provide energy for use by the plant (See Figure 2). Photosynthesis transforms radiant energy from the sun into chemical bond energy within the carbohydrate molecule. The chemical bond energy is transformed to a smaller unit of energy within the ATP molecule. The energy within the ATP molecule produced during cellular respiration allows

photosynthesis to continue. The two processes occur simultaneously, and continuously with variations, throughout the life span of a green plant.

-----[Insert Figure 2 here]-----

Photosynthesis and cellular respiration are described as “opposite” at the biochemical level (Canal, 1999) and yet are complementary on the global level (see Figure 1). A focus on the biochemical level while ignoring flow of matter (Wilson et al., 2006) may lead to the simplistic conclusion that the two processes are literally opposite. This misconception may indicate a perceived disconnection between the biochemical and global levels, thus isolating their respective functions. Chi’s (2001) criterion of complexity is that emergent mechanisms unite the various ecological levels within a system. This is certainly the case with photosynthesis and respiration. The energy reaction is the “emergent mechanism.” Explanations of this phenomenon that focus only on the organism or biochemical level fail to account for the emergent mechanism.

Learners’ Conceptions of Photosynthesis and Cellular Respiration as Systems

Extensive research has been done on students’ conceptions of photosynthesis and cellular respiration (e.g. Bell, 1985; Wood Robinson, 1991). Fewer studies have been conducted on these processes from a systems view or the interconnectedness. It appears that learners either see no relationship between the processes (Songer & Mintzes, 1994) or see them as inverses of the same process (Canal, 1999). In a review of the literature, Canal (1999) found the misconception of photosynthesis as “inverse respiration” begins in middle school and continues throughout high school. Research is lacking on when, if, or how this misconception may change.

When considering the system view, the research indicates minimal to no understanding across multiple ecological levels. Waheed and Lucas (1992) found that 93% of students (ages 14-15 years) understood the ecological level. Twenty percent showed understanding at the

ecosystem level. Only five of their fifty six subjects showed understanding of the processes at four levels (biochemical, cellular, organism, and ecosystem).

Lin and Hu (2003) also recognized the need to approach both processes as integrated systems. They investigated category frameworks of seventh grade students, and considered “phenomenal knowledge” or knowledge regarding organisms; “mechanical knowledge” or knowledge regarding cells; and “physical knowledge” or knowledge regarding molecules. Their participants had weak understanding of the integration between systems. Lin and Hu recommend an integrated instructional approach which covers at minimum all three frameworks of knowledge and the inter-relationships.

Barak, Sheva and Gorodetsky (1999) argue that biology is difficult because curriculum focuses on matter, not processes. They asked tenth grade students to “comprehensively justify” their responses on a questionnaire with four open ended questions. One question was “why are the green plants in the base of the ecological pyramid?” Significant for this study is that forty percent of the responses (from more than one hundred) did not regard photosynthesis as having any relationship between the living and non-living world. The authors concluded that matter-based language is indicative of a simplistic understanding of biology. Process-based responses reflected a more meaningful level of understanding. These authors recommend a systems approach to the teaching of biology, suggesting explicit instruction in the inter-relatedness among systems. A similar recommendation is made by Wilson et al. (2006) who incorporated assessments into an undergraduate biology course to challenge students to track matter across system levels.

Preservice Teachers’ Science Content Knowledge

In *Examining Pedagogical Content Knowledge*, Gess-Newsome (1999) asserts that teachers must hold “deep and highly structured content knowledge that can be accessed flexibly

and efficiently for the purposes of instruction” (p. 53). Gess-Newsome refers to the notion of compartmentalizing concepts as having a “content-specific teaching orientation” (p. 57). Even when confidence levels are high, most preservice teachers have a limited understanding of the content they are to teach in a “conceptually rich or accurate manner” (p. 57). Their knowledge is often fragmented, compartmentalized, and poorly organized, making access very challenging. Within this perspective, preparing to teach at the elementary levels can be daunting given that elementary teachers must have command of multiple subject matters. Regarding science, elementary teachers generally have concerns about their subject matter knowledge (Abell & Roth, 1992; Appleton, 2007), and these concerns often relate to their beliefs and confidence regarding science teaching and learning (Akerson & Flanigan, 2000; Cakiroglu & Boone, 2002; Harlen, 1997; Schoon & Boone, 1998). Teacher educators need to understand how future elementary teachers conceive relevant science content, and explore how this knowledge represents awareness of biological systems and connections among them. The current study begins to examine such conceptions as they relate to photosynthesis and cellular respiration.

A Framework for Justifying Conceptions

The present study also aims to describe how preservice teachers rationalize, or justify, their conceptions of photosynthesis and cellular respiration. The work of Tamir & Zohar (1991) and Southerland, Abrans, Cummins and Anzelmo (2001) provided the framework for this portion of the study. Southerland *et al.* (2001) used reasoning strategies to categorize students’ ideas about biological processes. Student explanations included: applying human attributes as a causal agent (*anthropomorphism*); using the end result as the causal agent (*teleological*); applying circular reasoning (*tautology*); and using a specified divine agent (*pre-determined*). The students also used forms of *mechanistic* reasoning to explain biological processes. *Mechanistic proximate*

reasoning suggested attention to only one ecological level within the system. *Mechanistic ultimate* reasoning expressed more of an interactive or systems-based explanation.

Research Questions

1. How do preservice elementary education students conceptualize the relationships of photosynthesis and cellular respiration with respect to (a) inter-connectedness between the processes, (b) working on multiple ecological levels, and (c) being components within “nested systems”?
2. What justifications do preservice elementary teachers provide to support their conceptions of photosynthesis and plant cellular respiration?

Methods

This qualitative study relied on multiple data sources, with the intent of triangulating and providing a convergent validation (Berg, 1998). The primary researcher collected data through explaining sets and cognitive and clarifying interviews. Validity of all data collection procedures toward intended goals was established by a panel of biologists and biology educators. Figure 3 provides a summary of the data collection instruments, the research design, and the data analyses. Figure 4 illustrates the relationship between field observations and data collection, and also indicates the number of participants who participated in each collection session.

-----[Insert Figures 3 & 4 here]-----

Context of the Study

This study was situated within the context of a nine-week biology content course designed for elementary education majors at a midwestern university. All 18 students enrolled in the course participated in the study, although not with all instruments. Participants ranged from recent high school graduates to non-traditional college-aged students seeking second careers.

Data used to understand the instructional context included class materials, classroom observations, and instructor interview. These sources were not used to answer specific research questions, but to understand the context and implications of findings. Instructional materials, including texts and course handouts, were examined to determine the extent to which they considered systems with respect to photosynthesis and cellular respiration. The text explained the purposes of the processes through narratives (AAAS, 2004) with a step by step approach, beginning at the organism level and moving quickly to the biochemical, with some mention of relevance on an ecological level. None of the class materials contained explicit explanation of “systems” with respect to photosynthesis and plant cellular respiration.

Instruction on photosynthesis and cellular respiration comprised three lectures and one laboratory period. The lectures were teacher-centered, direct instruction sessions. There was a single laboratory activity related to cellular respiration and photosynthesis. The instructor began the laboratory instruction by stating, “Plants, like animals, have cellular respiration.” The students then tested for the presence of CO₂ in live and heat-killed sterile corn seedlings; they compared two plant leaves (one kept in the dark, one kept in the light) for presence of starch (iodine test) and glucose; and they examined variegated leaves. In the laboratory assignment, students were asked to elaborate on the biochemical level of both processes.

The course instructor was interviewed at the completion of the course and data analysis. The purpose of the interview was to gain insights into instructional intent and to inform possible implications of our findings for classroom instruction.

Data Collection

Explaining Sets

Sixteen of the 18 preservice teachers participated in the explaining set process. The primary researcher, in consultation with the course instructor, placed participants in dyads. The

dyads comprised students who the instructor considered compatible to discuss science content. The participants were asked to conduct each task, and talk with each other about their ideas and decision-making. Participants were to take turns in explaining, alternating who began each task. Participants were asked to make their explanations at least thirty seconds in length, and to define any scientific terms they used. There were four tasks in total.

Task 1.

The “warm-up” task was designed to establish both a talk-aloud protocol and a procedure of alternating explanations. Participants assembled an Escher tessellation puzzle while explaining what they were doing and why.

Task 2.

The “plant comparison” task asked for an explanation of plant growth. Props included two plants of the same species but of different sizes. This scenario was designed to determine if participants could conceptualize the plant as a biological system, and plant growth as a function of a global atmospheric system. It also intended to reveal if participants could connect plant growth and other metabolic processes such as photosynthesis with plant cellular respiration. A sample question read “Explain any special conditions or requirement that the plants needed in order to be the way they are now. Please tell all the details you know.”

Task 3.

The “ecosystem in a jar” task presented participants with a clear plastic jar containing plastic plants and two figurines of people. They were asked to imagine the objects as living and life sized, and to explain their vision of the future for organisms in the jar. This task was to determine if the participants could explain the products and processes of photosynthesis and respiration, and if they viewed them as inter-connected and independent of human activities. Accompanying questions asked for reflection on how they conceptualized the two processes. A

sample question read “Explain the relationships that are going on in the enclosure. Explain your response thoroughly.” This task elicited ideas related to multiple ecological levels, or biological systems within a global system.

Task 4.

The meta-representation task required participants to draw a representation of a “plants’ role in the natural world.” The design for this task is based on diSessa’s suggestions for meta-representation of intuitive knowledge (diSessa & Sherin, 2000). Each individual participant explained his/her meta-representation to the researcher. The explanation served as a validity check, reducing the potential for interpretation based solely on artistic ability or researcher assumptions.

The primary researcher was a passive observer during tasks 1-3. Field notes described interactions between participants, and also included notes regarding their conceptual understanding. These notes helped to guide construction of probing questions for cognitive interviews. All sessions were video and audio taped, and later transcribed for analysis.

Cognitive Interviews

Fourteen participants agreed to the cognitive interviews. The sample comprised both high achieving students and low achieving students (based on course grades and participation), representing a range in understanding of photosynthesis and plant cellular respiration. The interview probed views of both plant processes, using two plants as props. Initial interview questions were based on notes from the researcher’s journal and explaining set transcripts. Additional questions arose as needed for clarification during the interview. Questions concentrated on how participants conceived the plant as a biological system, plant growth, and plant interactions within and between systems. Participants were asked to describe both photosynthesis and cellular respiration and to consider what would happen if either of the

processes was disrupted. A sample question read “How do you think the organelles within the plant play a role in photosynthesis and cellular respiration?” Participants were also asked to reflect upon why they hold their particular ideas. They were asked such questions as, “How did you come to know about plants and what they do?” and “How do you come to accept these ideas?” Transcriptions were made from video and audio recordings. Research notes were taken during these sessions, and read by the researcher prior and following each collection.

Clarifying Interviews

Seven participants participated in the final clarifying interviews. These interviews were conducted after preliminary analysis of the explaining sets and cognitive interviews. Several of the remaining participants expressed scheduling issues as a reason for not participating further. This third interview provided an opportunity to clarify participants’ conceptions and justifications. During the cognitive interviews, we noted that participants often made reference to images that had been presented in their course lecture or text. The preservice teachers expressed frustration at “seeing” a mental image associated with their classroom instruction, but being unable to explain their conceptions without the image. A similar pattern emerged regarding vocabulary. Participants articulated a “tip of the tongue” phenomenon when they wanted to use a term from the unit, but could not recall the term. In the clarifying interview, we provided copies of many of the images found in the text and lecture presentations, as well as vocabulary words that participants had used during cognitive interviews or explaining sets.

Questions for the clarifying interview stemmed from an initial review of the explaining sets, cognitive interviews, and researcher journal. A typical question began with the phrase, “Earlier, when we talked, you mentioned” We asked the participants to elaborate on their earlier idea. Two questions were asked of all participants during the clarifying interview: “What do you think a life cycle or a cycle is?” and “What do you think a biological system is?” We had

earlier noted variance in participants' use of these terms as they were applied to plant processes. As this final interview proceeded, follow up questions enabled further clarification on their ideas and researcher interpretation.

Data Analysis

Informal data analysis was conducted simultaneously with data collection, and recorded in narrative form in the researcher journal (Creswell, 1994). Data were reduced and organized through sorting, categorizing and formatting information. *Ethnograph* (Qualis Research Associates, 1998) qualitative analysis software allowed for organization of the data and frequency information. The unit of analysis was the individual, with results combined to describe the population of the class. Data analysis included both reduction ("de-contextualization") and interpretation ("re-conceptualization") resulting in a larger constructed image of the preservice teachers' conceptions of the plant processes. Data were reviewed for reference to photosynthesis and cellular respiration in general, as well as the extent to which participants viewed the processes as inter-connected and occurring both on multiple ecological levels and within "nested systems." Analysis targeted justifications for views, guided by the categories of Southerland et al. (2001). Cycles of data review and reduction resulted in final categories to answer the research questions. The results section provides representative passages expressed directly by the preservice teachers to substantiate the researchers' interpretation of the data.

Results

Participants held varied conceptions of the two processes. Individual's conceptions did not appear to vary over the duration of the project. Overall, participants tended to focus on individually relevant facets of the processes, suggesting compartmentalized views with minimal recognition of connections within or across levels of biological systems. We describe their views and justifications here. Even though general categories of conceptions emerged, any individual's

responses could be sorted into more than one category. While this may be interpreted as a weakness in the analysis, it is more likely reflective of the in-depth nature of data collection, involving multiple conversations on a single topic over a four week period. The results are organized based on the research questions. First, we present results describing how conceptions fit within the framework of a systems view (interconnections between the processes, on multiple ecological levels, and occurring within nested systems). Second, we describe the explanations participants provided to support their views.

Conceptions of interconnectedness, multiple ecological levels and “nested systems”

Inter-connectedness

All participants affirmed that photosynthesis and cellular respiration were plant processes. In addition to the instructor explicitly telling the class that plants do both processes, the laboratory activity required them to test for both CO₂ and O₂. For all but two participants, conceptions did not advance beyond affirming the existence of both processes within the plant system. Most participants were able to describe components of the two processes but could not describe how the processes connect.

Lack of knowledge

Five of the 18 participants (27%) lacked knowledge of the processes beyond simple book equations or analogies (e.g. breathing). They struggled to describe the processes in their own words. They reportedly found photosynthesis confusing and could not describe if or how it related to cellular respiration. The following exchange from Betty is representative of the confusion.

Researcher: What about plants do you find confusing?

Betty: I guess just exactly how photosynthesis occurs...Right, exactly how it occurs. I know how it occurs in a book, or on a piece of paper, I can understand

that, but just exactly how the cells work. I know that, it's just....I don't see how they can do that.

Betty's response suggests that although she feels somewhat comfortable with the book version of photosynthesis, which is a biochemical equation. She struggles to envision the process at the cellular level, and does not conceptualize how components of photosynthesis and cellular respiration relate. She appears to disassociate the book version from the physical process that occurs in a real cell.

Two participants reported they did not know enough about cellular respiration to say anything about the process, let alone how photosynthesis related. Only two suggested plants were undergoing cellular respiration when asked, "What are the plants doing?" One of those responded, "Breathing," but could not elaborate her meaning.

Processes as Energy Reactions.

Photosynthesis was seen as the energy process. Ten (55%) provided evidence from food chains and light energy to support their view. For example, Anita suggests that the sun ultimately enables photosynthesis. Anita suggests that while the sun is the source of energy for the plant, the plant plays a producer role within the food chain.

I mean the sun, is basically, I don't know, a big factor in life, because without the sun, a lot of things wouldn't be able to produce, like corn, and stuff that we eat, vegetables, and the grass that cows eat, which we eat the cows, so a lot of things wouldn't be able to be produced, and we would have to use what we have left and after that, we wouldn't be able to live.

Participants often stated sunlight as a source of energy, but could not contextualize their description at a biochemical level. Although the reactions were taught at the biochemical level, no participant mentioned electrons being excited in the process. Furthermore, even though they

conceptualized photosynthesis as an energy process, their descriptions were not necessarily scientifically accurate. For example, Vera describes photosynthesis as the process of turning light into energy that plants use.

(Photosynthesis is....) A certain amount of energy out of the light, which is called ATP, into taking the light, and turning it into energy, and the energy that plants use is glucose.

Three participants describe cellular respiration as an energy process. They did not necessarily conceptualize the reactions as serving an end in the same way photosynthesis seemed purposeful. They struggled to describe the relationship between energy and food.

Cellular respiration is...basically taking the energy out of the food molecules and food itself and that is being converted into um, ah...I don't know what kind of energy it is being converted to....chemical energy?

Well, this is what I understand of it, photosynthesis breaks down, like, um, carbons and makes energy and stuff, and um, to get the product back into the glucose, the six carbon sugar, then they use cellular respiration.....then you have like the products, which is energy, and then you needed that to make food, so cellular respiration is taking that energy back into making food, and that's the cellular respiration.

Notice photosynthesis and cellular respiration are described as being two different processes, serving opposite purposes. The former is responsible for breaking down carbons, making energy and “stuff” while cellular respiration “is taking the energy back into the food.” There is some notion of connections between the processes in terms of food and energy, but the conception is ill-formed.

Processes as Gas Exchange Reactions.

Participants used various descriptions of gas exchange to describe the processes, sometimes suggesting connections between them and sometimes suggesting isolation. Two participants identified photosynthesis as a process for producing oxygen. This role was seen as a purposeful event, i.e. "They give off oxygen, which we need to survive." They knew photosynthesis released oxygen, but regarded oxygen and carbon dioxide exchange as cellular respiration. These participants did not recognize the inconsistency of their ideas. Instead, they suggested that photosynthesis released oxygen, and cellular respiration was the gas exchange reaction, taking in carbon dioxide and also releasing oxygen.

Only three participants noted the role of carbon dioxide as a component of photosynthesis. While no one was able to successfully associate carbon dioxide directly with cellular growth, one participant identified carbon dioxide as a source of oxygen. The oxygen/carbon dioxide exchange was described as cyclic between plants and humans. These ideas indicated connections between photosynthesis and human respiration, but specific connections between photosynthesis and *plant* cellular respiration was not evident.

I would say that um, the plants are providing oxygen for the people, and the people are providing the carbon dioxide for the plants, that they need for photosynthesis.

Well, with the oxygen, plants give off O₂, like, you know while they are going through their phase of photosynthesis. They give off oxygen, in order for them to have carbon dioxide, in order to give off oxygen, and they go through certain cycles to do all of this.

Five participants described a reaction in which the carbon was simply removed from carbon dioxide which then changed into free oxygen. This idea was the most common

conception of cellular respiration in the sample. When asked, “What is cellular respiration?” Vera responded, “The transfer, the transformation of CO₂ into oxygen. They respire oxygen.”

Three participants reported that cellular respiration is a mechanism for releasing carbon dioxide. They held varied ideas of the actual release mechanism. Nan suggested photosynthesis and cellular respiration are opposites in that one produces oxygen and the other produces carbon dioxide, “Just like breaking down your food, the glucose and putting it into CO₂.” Anita stated that cellular respiration comes directly after photosynthesis when “giving off carbon dioxide.” All of these descriptions suggest the participants held misconceptions about the biochemical processes and flow of matter through the systems.

Photosynthesis as a food/growth process.

Five participants equated photosynthesis with a food or growth process. Although their ideas included knowledge of plant growth, food production was seen as a service to other organisms. There was no evidence that these participants perceived plants as independent organisms themselves. Moreover, these five also suggested that plants make their food from nutrients in the soil, a common misconception. In general, the participants could not distinguish between “food” and “nutrients.” Half of the preservice teachers indicated that they did not know how the plant used photosynthesis to grow. Without such understanding, they were unable to make coherent connections between photosynthesis and plant cellular respiration.

Connections between the processes.

Only two had a partial idea of how the processes are connected. Ann explained both processes as energy reactions, but struggled as to why a plant would need both. The confusion may lie in her concept of food. She defines photosynthesis as a way to “make, um, food and energy for the plant.” When asked if those are two separate items, food and energy, Ann responded,

I don't know how to explain food and energy. It's just we eat for energy, and then there is like energy of ATP, and it makes like food, so. And, then food is used to make energy, so. Hmmm, that is very complex there.

Another participant connected cellular respiration and photosynthesis through the mutual use of oxygen, but had less conviction about his conception. He identifies oxygen as a shared component but fails to describe how oxygen functions within the two processes or describe a connection of the processes to energy. There is little indication that he understands photosynthesis and cellular respiration as processes connected within a system.

I can't really see it. I mean the main things I can explain, they both (do) photosynthesis and cellular respiration, and they both have to do with oxygen.

In summary, when comparing photosynthesis and cellular respiration, participants described photosynthesis as the energy reaction, and cellular respiration as the gas exchange reaction. The connection between the two processes was affirmed by most, but when probed to explain the nature of the connection, the participants struggled. They tended to view the connection as embodied in the "opposite" nature of the biochemical reactions. Further, they tended to describe photosynthesis as a means of oxygen production for use in animal respiration. The limited understanding of the interconnections between photosynthesis and plant cellular respiration may be a consequence of their limited understandings of the individual processes.

Multiple Ecological Levels

Conceptions related to ecological levels were determined by the extent to which responses focused on different levels during the explaining set and interviews. Responses that focused on the biochemical level included references to such ideas as "the hydrogen ion gradient" and "it needs energy in the form of ATP." Responses such as "This process happens in the mitochondria." were categorized at the cellular level because of connections to cellular

organelles. Participants who focused on the organism level described the plant, or used phrases that included structural components of the plant, such as leaves and roots. Responses typical at the ecosystem level referenced the role of plants as part of the larger food chain, and as affecting the community surrounding the plant. Global level conceptions included phrases such as “adds oxygen to the whole atmosphere” and “it balances the environment.”

Figure 5 provides ideal explanations for photosynthesis and cellular respiration for the purpose of comparing the responses. Table 1 summarizes these results. Placement is not indicative of accurate scientific conception, but rather indicates provision of a response referencing a specific ecological level. For example, when asked how a plant would grow, Shirley responded, “You plant a seed, water it, and sunlight and it grows.” This response was categorized at the organism level (seed and statement of basic plant needs).

In examining all the responses, the most common level represented related to the organism (83% of the participants). Fifty-five percent of the participants referred to connections of the processes to the global and/or ecosystem levels. Least frequent were connections within the biochemical level (39%) and cellular levels (22%). Only four participants (22%) were able to discuss the processes at all five levels.

-----[Insert Table 1 and Figure 5 here]-----

Despite referencing the biochemical level, few participants were able to adequately explain the processes at the biochemical level. For example, Bob contextualized the processes within the biochemical level, but did not capture the essence of the connection:

Well, in the Calvin cycle, right after that, the respiration occurs, and releases hydrogen, and H₂O is a by product of that. And, ah, you're just trying to free up electrons, so the oxygen is splitting or the water molecule is splitting again, and

the hydrogen goes one way, or no the hydrogen goes back in, and the oxygen is breathed out. That's how it's done. So, oxygen is the by-product.

Bob fails to describe photosynthesis and cellular respiration as occurring simultaneously and continuously. He misses the link of glucose and ATP production between the two processes. We can compare this type of conception to Figure 2. The Calvin cycle is a photosynthesis component. The electron transport mechanism includes the splitting of hydrogen using oxygen in cellular respiration. Oxygen is a by-product of photosynthesis. While Bob is attempting to connect the two processes at the biochemical level, he still maintains that photosynthesis is the energy reaction, while cellular respiration has a purpose in gas exchange. Although the biochemical level was rarely referenced, all participants were taught both processes at that level.

Suzy and Kay did not provide enough evidence in their responses to place at any particular level. Kay considered both processes too abstract and was not able to describe them:

Researcher: What kind of things does [the plant] need to be able to grow? Is it doing those things?

Kay: I don't know. You probably can't see what it does.

Researcher: Are there things that take place that you don't see?

Kay: When they absorb the light, you can't really see when they do that, but they do.

Nested Systems

Only two of the eighteen participants, Ann and Bob, suggested a scientifically accurate conception of nested systems. Three others said they did not know what a system is, and they did not attempt an explanation. The remaining preservice teachers provided evidence that they understood that systems involve interactions among components, but they did not extend their ideas to include the notion of a system within a system, or "nested systems."

Ann referred to nested systems when she discussed her meta-representation (from Task 4) of a plant's role in the natural world (Figure 6). Ann's drawing shows a globe, a tree with fruit, and the cellular structure of the trunk. She described her meta-representation as,

...you have a sun, you have an earth and the trees, and in the trees you have cells, that have the energy, and the cells would break down into organelles and atoms...and the littlest part has to work for the biggest part to work. The biggest part has to work for the littlest part to work.

-----[Insert Figure 6 here]-----

Although the concept of "nested systems" was not explicitly taught to the participants, both instructor and text implicitly described interacting sub systems. The instructor provided laboratory experiences, stressing the necessity of the biochemical processes for the organism level. The text provided illustrations showing biochemical reactions and cellular organelles telescoping from a plant organism.

Emergent Themes from Research Question One

Three themes emerged to describe how the participants view the biochemical processes as they relate to the world in a broader sense. The themes were egocentrism, interdependency, and a sociological view.

Egocentrism.

Participants repeatedly referred to plants as organisms that provide a service to humans. Photosynthesis and cellular respiration were involved in this service. Participants placed humans as beneficiaries of the plant processes, but did not necessarily conceive of plants as organisms with metabolic needs in their own right. Anita explains this idea at the biochemical level.

The carbon is taken away, and the plants use it for something else and in the end, oxygen comes out, and they are now giving off oxygen, which we breathe.

When questioned later about the role of plants; she clarifies, “Well, the major thing is to give off oxygen to us human beings.”

Meta-representations were consistent with an egocentric perspective in showing plants providing shade, food, and oxygen, directly for people. Recall Ann, the preservice teacher who could conceptualize the processes on multiple ecological levels, and as nested systems. She, too, held an egocentric view.

..... and with them (plants) giving off oxygen and that, um, that (process) helps our ozone layer, with us giving off CO₂, they can use that and give us back oxygen, cause that's what we need to live, so with us, given off so much CO₂ and stuff, we need a lot of plants to help balance our ecosystem, so that we don't end up with no ozone layer and all die.

Interdependency.

Not only were plants viewed to be in service to humans, plants were also seen as dependent *upon* humans. All the preservice teachers expressed an “interdependency” that was viewed as the “balance of nature.” Humans provide CO₂ for plants, and plants provide oxygen for humans. There was an expressed need for human intervention in the life of plants. Humans care for plants by providing water, and nutrients in the form of food, as well as soil, and carbon dioxide. Participants could not describe a situation where plants could survive in the absence of humans. This perspective of interdependence is naturally related to egocentrism. When explaining her meta-representation, Shirley stated:

.....you know, people have plants in their homes to make it look nice, and calming, and also, the plants, also help, you know in breathing. And, I drew the people helping the plant by giving off the CO₂

Sociological View.

Participants suggested a societal need to care about plants. Plants provide a service to individuals (egocentrism again), but also benefit human society as a whole. We considered such responses indicative of a sociological view. Plant interactions within the ecosystem were considered necessary for providing food. One example given was the role of pollination in sustaining plant life. Plants were also seen as necessary for the mental stability of humans, to prevent boredom and give “beauty” to the natural world. When speculating about potential problem associated with an over-or under- abundance of plants, the participants described societal needs first. They described that plants could “over populate the people” within the ecosystem, and “suck the ground dry from water;” people “need self discipline” to care for their habitat or a more “primitive society” would emerge which would ignore civil laws. The preservice teachers held conceptions of an ecosystem that required careful manipulation in order to meet the needs of society.

When responding to the question of long-term effects of an ecosystem, Kurt and his dyad partner Kay provided this perspective:

Kay: As time passes, [people] are going to have to limit, maybe learn to limit a little, not go excessive in what they are eating, but, and they also are going to have to maybe restrict to just um, like, a vegetable and plant kind of diet.

Kurt: ...Like from the aspect as far as they having some self discipline, it's kind of like human nature has a tendency to kind of want, when it's unlimited we kind of want to indulge in it, and then it's like you have to know when to say no, and when to say yes.

This sociological theme was less common than egocentrism or interdependency. Nonetheless, this view was promoted by a majority of preservice teachers in this sample.

Justifying Conceptions

The contexts for justifying views tended to reflect participants' nominal knowledge of the processes. Nominal knowledge was particularly evident when referencing the biochemical level, with participants unable to distinguish between carbon and carbon dioxide; and at the cellular level, with confusion between chloroplasts and chlorophyll. The majority of participants had nominal knowledge of one or both processes and/or was challenged by vocabulary.

Categories from Southerland *et al.* (2001) guided our analysis of justifications. These categories (authoritarian, anthropomorphism, teleology, mechanistic, and tautology) describe how the participants justified their conceptions of the two biochemical processes and the relationship between them. Circular reasoning (tautology) and using a result to explain a process (teleology) were not always clearly discernable from nominative knowledge. As such, quantified values may be more reflective of their limited knowledge of the topics.

Authoritarian

Although there were less than twenty total citations of authoritarian sources, they were more distinct than those from other reasoning modes. They were also more easily discernable from nominal knowledge. When asked how they knew specific details about the two processes, a commonly cited source was classroom instruction (an instructor, laboratory activity, a text,).

Well, I don't think the teacher is going to get up and just lie about something.

So, I mean like right now, I can go by what a teacher tells me until someone else tells me different. So, I just go by what I read and by what I'm taught, before I learn something differently.

Participants also cited experiences with relatives. They mentioned gardening with grandparents, as well as personal experiences with houseplants. When asked about how they

knew about plants, the majority mentioned some physical activity in which they had been engaged.

Anthropomorphism

There were more than fifty instances of participants assigning human attributes to plants, as evidenced by the aforementioned responses relating to “plants breathing.” For example, Bob describes how plants use “food from the soil.” In his response, the causal agent has human characteristics whereby plants eat in a similar manner to humans.

...um my favorite meal is steak. <laughs>. I don't know what their favorite meal is but I know they like nitrogen, they like sulfur, they like, what is the other dissolved mineral in the soil?

Teleology

Some justifications for differences in plant sizes suggested a teleological rationale. There were 51 instances of such rationale. In one of the more distinctive examples, Joy explains one plant's fuller shape. In her comment, Joy suggests light produces growth; therefore, if the light were all around the plant, it would grow fuller by design.

It [the bigger plant] obviously is more full. Like, maybe the light source is coming from all around it or something. So the plant kind of grew out towards the light.

Mechanistic

Thirty-two explanations suggested a mechanistic understanding of the two processes, but focused primarily at the ecological level of the organism. They rationalized a plant's condition by attributing appearance to lack of water, nutrients, and sun. Those mechanistic *proximal* responses accounted for the majority of recorded incidents. Less common were explanations involving genetic variability. Statements such as “maybe this plant is a dwarf species” were recorded as mechanistic *ultimate*.

Tautology

Explanations were sometimes so circular that the reasoning was difficult to follow. For example, one participant stated that the plant grew because of photosynthesis and photosynthesis was happening because the plant grew. One participant confused starch, glucose, and energy when tried to explain plant growth through his recollection of the laboratory experience. That confusion is further expressed when he links ATTP (a vocabulary error) with PHP ATP (another vocabulary error) and cell reproduction.

We had a starch test, a Benedict's test, and that, it had less starch or glucose; it would stop producing energy, and energy source, glucose. In turn, that would slow down all the energy that the mitochondria can, you know, use, and the ATP production would slow down. And once the ATTP production would slow down, the PHP ATP production would slow down, and um, you just wouldn't be able to reproduce cells, and it wouldn't grow.

Intuitive conceptions: Using knowledge of human systems to justify conceptions of plant systems

Some justifications did not appear to fall into any established category and appeared to be more intuitive. According to Southerland *et al.* (2001) such

...explanations are understood to be fluid because they are constructed on the spot, in direct response to the very particular cues of the biological phenomenon and the interview questions. Thus, students' explanations might not be an exclusive reflection of ill-formed-but-existing conceptions rather, they are spontaneous constructions. Using this theory, students are not thought to hold preformed, static conceptual frameworks for all topics. (p. 343)

All the interview settings probed ideas about the role of plants, including comparisons with humans, but the majority of responses emerged during the explaining sets. During our explaining sets, pairs of students justified their responses to each other. This exercise may have provided a comfortable setting conducive to eliciting such conceptions. We note that these responses also reflect anthropomorphic views. Comparing human and plant structures and functions seemed to be a valued means of justifying conceptions.

When Charles explained a plant's role in the ecosystem, he stated:

Just like a person would, it respire, we breathe out carbon dioxide, they breathe out oxygen. So probably not all that different other than they way we get food and, you know, the way we live. We're obviously a little bit more mobile than a plant, but so, not all that different.

Kurt compares plants to humans at the cellular level.

Um, well, I mean, I know one main difference is that um, like, humans for instance, we don't have a cell wall, and I think plants have, um, you know cell walls. We have pigmentation for our color, and they use like chloroplasts, so.

In his next comment regarding similarities, note Kurt's possessive use of "our" light source and suggestion plants may need "rest." This time his response is contextualized at the organism level.

They need sufficient light and water to survive, well, I believe all other life's organisms need our light source as well, like human beings, we need an ample amount of food, water, and rest, in order to survive and really function.

Carl starts his explanation of similarities by comparing plants and humans, but broadens the scope to include other organisms before refocusing on humans.

Basically, plants are made up of the same building blocks as everybody else, of molecules, cells, it takes all the same things to build a plant as it does to build a person, cat, dog, bird. We're just about all the same things, with just a few minor differences between each of us. A different little cell here, a little cell here and you're a plant, and you're green.

The preservice teachers frequently used themselves or humans in general, as a point of reference. They attributed human characteristics to plants, and identified parenting skills, intelligence, intent to their actions, and other human attributes in plants.

Obviously, their atmosphere, their conditions to grow, so, ah, they can't think. Really, I mean, plants are, they don't have a brain, so they don't necessarily know. But, they are like a, they are like a... the parents of a plant have to care for them in order for them to thrive, and that is similar to others...

Participants referenced prior experiences that influenced their conceptions, even reaching back into their elementary years. In some cases, those earlier experiences held more weight than current instruction. During classroom instruction, prior knowledge about the topic was never considered; the instructor did not ask her students to reflect on common experiences. Yet, the participants in this study apparently did so when they searched to justify a response. Intuitive conceptions provide further evidence of an anthropomorphic theme. If participants use "self as first referent" when they consider the processes of plants, a logical next step may be to anthropomorphize the plant with human characteristics. The combination of anthropomorphic reasoning and intuitive conceptions give further evidence to the egocentric theme of their conceptions. Apparently, participants viewed plants from their own perspective, applied a limited number of human characteristics, and judged them to be useful to humans within the ecosystem.

Discussion

The results of this study contribute to our understanding of future teachers', and undergraduate non-biology majors', conceptions of photosynthesis, plant cellular respiration, and the connections between these processes within and across multiple ecological levels that comprise nested systems. The results demonstrate that despite being able to restate the biochemical formula for the processes, these undergraduates struggled to conceptualize how the processes were interconnected by means of matter. They could affirm that the processes were connected, but were unable to adequately explain the nature of the connection. Moreover, they struggled to conceptualize how the reactants and products of the processes related to the cell, organism, local and global ecosystems. They tended to hold on to concrete ideas related to the organism, the plant (Table 1). With just a few exceptions, they lacked meaningful conceptions related to the cellular and biochemical levels. They demonstrated more misconceptions about process functions at these levels. Many of the misconceptions identified within this study have been previously described (e.g. Anderson, Sheldon, & DuBay, 1990; Bell, 1985; Canal, 1999; Driver, Squires, Rushworth, & Wood-Robinson, 1994; Waheed & Lucas, 1992).

The preservice teachers suggested a broader sociological view than was provided in their instruction, relating concerns of overuse, and the need to preserve habitats for others. These preservice teachers had a sociological view of a plants' role in the ecosystem. They also had egocentric and interdependence views of plants, especially plant dependency on humans. The notion of plants' existence contingent upon the presence of humans is consistent with Cakiroglu and Boone's (2002) findings. Novel to the present study is the role of plants being directly tied to the value of their service to us. The sociological, egocentric, and interdependent nature of the views expressed in the present study helps to explain their abilities and challenges with connecting the processes across multiple ecological levels. The most common level context was the organism, followed by the ecosystem and global contexts. These views seem consistent with

their human and societal concerns. Finally, the biochemical and cellular levels are least represented. The participants' ideas do not consider influences of these levels to humans or society. They lack a systems view that traces and connects processes across multiple levels. The sociological and egocentric perspectives may inhibit these learners from seeing connections or seeing nested systems. This finding may relate to these learners' abilities to utilize the principle of tracing matter (Wilson et al., 2006) when describing the processes or connections. Other than stating CO₂ comes from humans and is used by the plants, and oxygen comes from the plants and is used by humans, these participants paid little attention to origins or destinies of the matter involved in the processes. Similar findings have been reported for younger learners (Driver et al., 1994). Driver et al. suggests that the intuitive idea that the biomass of a plant comes from the soil, for example, is a consequence of the abstractness of the processes. To understand plants as dynamic complex systems, learners should be able to reason through multiple levels by means of tracing matter (Wilson et al., 2006). Our findings suggest that, like younger learners, these preservice teachers did not hold such a systems view. The possible relationships between egocentric and sociological perspectives and abilities to trace matter across biochemical to global levels should be further investigated.

Justifications fell within all the categories previously described by Southerland et al. (2001), including intuitive conceptions. Most clear were anthropomorphic, teleological, and authoritarian reasons. Others have described the prominence of similar reasoning in children (Driver et al., 1994). Why do these types of views persist? The participants in this study reportedly based their views on perceived instructional and personal experiences. Participants said the processes were connected because the instructor had told them so. The instructional context aids in interpreting these results. The instructor told her students that plants do both photosynthesis and cellular respiration. She also explicitly stated the two processes were

connected, explaining them as opposites of each other. Even though she may not have intended to didactically explain them as literal opposites, the students seemed to either infer this meaning or simply accept the statement that the processes are opposite. The participants had not been challenged to consider *why* and *how* the processes are connected to each other nor to other ecological systems.

The participants' logic suggests a "common sense" view (Ekborg, 2003), which has been associated with logic on surveys and interviews when taken out of the context of instruction. In this classroom, the concept of cellular respiration as an energy reaction may have been diminished when instruction focused on the more abstract cellular and biochemical levels. At these levels, cellular respiration was portrayed as a gas exchange reaction; confirming, perhaps, the intuitive conception of respiration in humans. "Breathing" in humans became analogous to "breathing" in plants. Our findings suggest that the preservice teachers relied on their "common sense" view when the topics shifted through multiple ecological levels and became challenging to explain. Implications for instruction are discussed below.

Model of the Preservice Teachers' Conceptions

Scientific research progresses by successive attempts to conceptualize process models (Cartier, Rudolph, & Stewart, 2001). Scientists identify patterns with and develop explanations of data. Models are created from identified patterns and provide explanatory and predictive frameworks for further study. Figure 7 is a schematic representation based on the patterns identified in this study. This is a preliminary model intended to help represent and explain conceptions of the processes across multiple ecological levels. It is our intention to use this model to represent our findings and as a basis for future research.

As discussed above, the majority of the participants conceptualized photosynthesis and plant cellular respiration through egocentric and sociological frames of reference. These two

perspectives are represented in the schematic as vertical bars in the background. Each ecological level (from Figure 1) is represented as a horizontal bar in Figure 7. Where the vertical and horizontal bars intersect indicates participants held views related to that ecological level and perspective. Figure 7 shows that participants focused on the organism, ecosystem and global levels. The cellular and biochemical levels were not as evident. Why? When we consider the learners' practical experiences, there are potential explanations and avenues worth further exploration. Considering the abstractness of each level, the organism may be the least abstract. We can touch plants. Movement in either direction from organism to global contexts or from organism to biochemical contexts increases the level of abstraction, with less opportunity for direct sensory input. Despite their abstractness, the ecosystem and global levels align with an egocentric and sociological perspective. Participants described common experiences they had or understood about plants within the ecosystem. They had heard about global environmental issues and the importance of human intervention. Perhaps the cellular and biochemical levels were too abstract to be compatible with participants' underlying perspectives (sociological or egocentric).

[Insert Figure 7 here]

A sociological view may be difficult to apply below the organism level. Rarely do societal needs list biochemical and cellular concerns as immediate societal needs include food, shelter, and water. If the frame of reference from which participants viewed photosynthesis and plant cellular respiration included societal needs, then ecological levels below the organism may have seemed trivial. In a similar fashion, an egocentric view may have little meaning below the cellular level. Participants may have focused on global, ecosystem and organism levels because of their intuitive tendency to use "self-as-first referent." "Self-as-first referent" may include a view of self relating to systems of human society, community, and organism; but not necessarily include self relating to cellular or biochemical systems. It may seem trivial to focus at the

biochemical level if the underlying view is from an egocentric perspective and the view of self lacks a critical biochemical component comprising simultaneous processes that connect across systems. A view of *self* as a system may help in the analogous view of other organisms as being systems (Eisen & Stavy, 1988; Stavy, Eisen & Yaakobi, 1987). A question for further exploration includes, “How do conceptions of interdependency, egocentrism, and sociological import influence conceptions of cellular systems and biological processes. Likewise, how does compartmentalizing the function and specialization of organelles at the cellular level influence the learners’ ability to explore connections with the plant’s role in the ecosystem and globally? Finally, the extent to which learners use “self-as-first-referent” with these and other biological processes should be explored further.

Implications for Classroom Instruction

Despite the instructor’s system objectives, her students did not achieve conceptual understanding of photosynthesis, cellular respiration, connections between the processes, or multiple and nested systems. We propose recommendations for instruction, all of which warrant further study.

Since learners impose anthropomorphic and egocentric reasoning, teachers might embrace the “self as first referent” intuitive conception through use of analogies. Instruction might use analogies, which may be intuitive, to assist in comparing the plant system with the human system. There is evidence in this study that participants intuitively compared plants to humans. If it is intuitive to compare plants to humans, then appropriately constructed analogies of system needs may be useful. This recommendation is made with knowledge of the cautions of Thiele and Treagust (1995) that analogies can cause misconceptions if analogue and source are not explicitly aligned. Dagher (2001) provides several approaches to instructional analogies

applicable to the study of these plant processes. One suggestion is the use of analogies in evaluation, which allows the learner to elaborate on their own self-constructed analogy.

If learners are to understand the complexities of biological systems (Barak, Sheva, & Gorodetsky, 1999; Carlsson, 1999) and the interactions among and across multiple ecological levels of systems, instruction as such needs to be purposeful and decompartmentalized (Wilson et al., 2006). Effective instruction should include explicit reference to systems, components, input and outputs, and emergent properties encouraging a systems view. Detailed signposts should be provided when moving through multiple ecological levels so that students are able to track the flow of components from one system to another. Questions asking forms and sources of matter and energy within and across systems should explicitly challenge learners to determine what components are involved, where they come from, and where they are going. Wilson et al. (2006) referred to this approach as the “tracing matter principle” and offer specific diagnostic tools to help instructors move learners toward a systems view. Finally, identifying a purpose and tying it directly to success of an entire system may present components as essential and interdependent, rather than disconnected and arbitrary. Learners may be less likely to compartmentalize components if each adds to the functional operation of an entire system.

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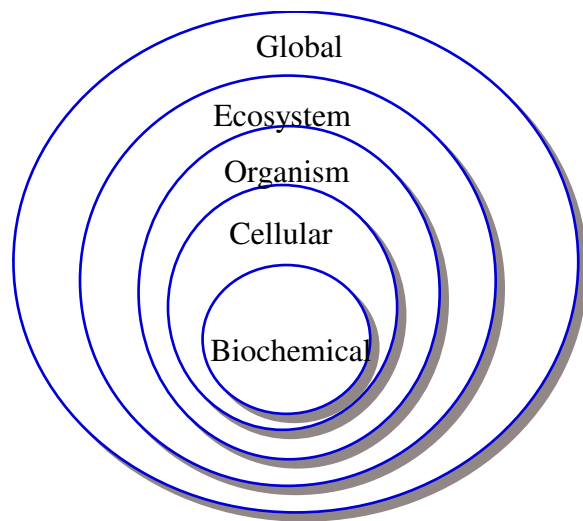
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CONNECTING PHOTOSYNTHESIS AND CELLULAR RESPIRATION

Figure 1: Multiple Ecological Levels as Nested System



Peer Review

Figure 2: Interconnected Plant Processes

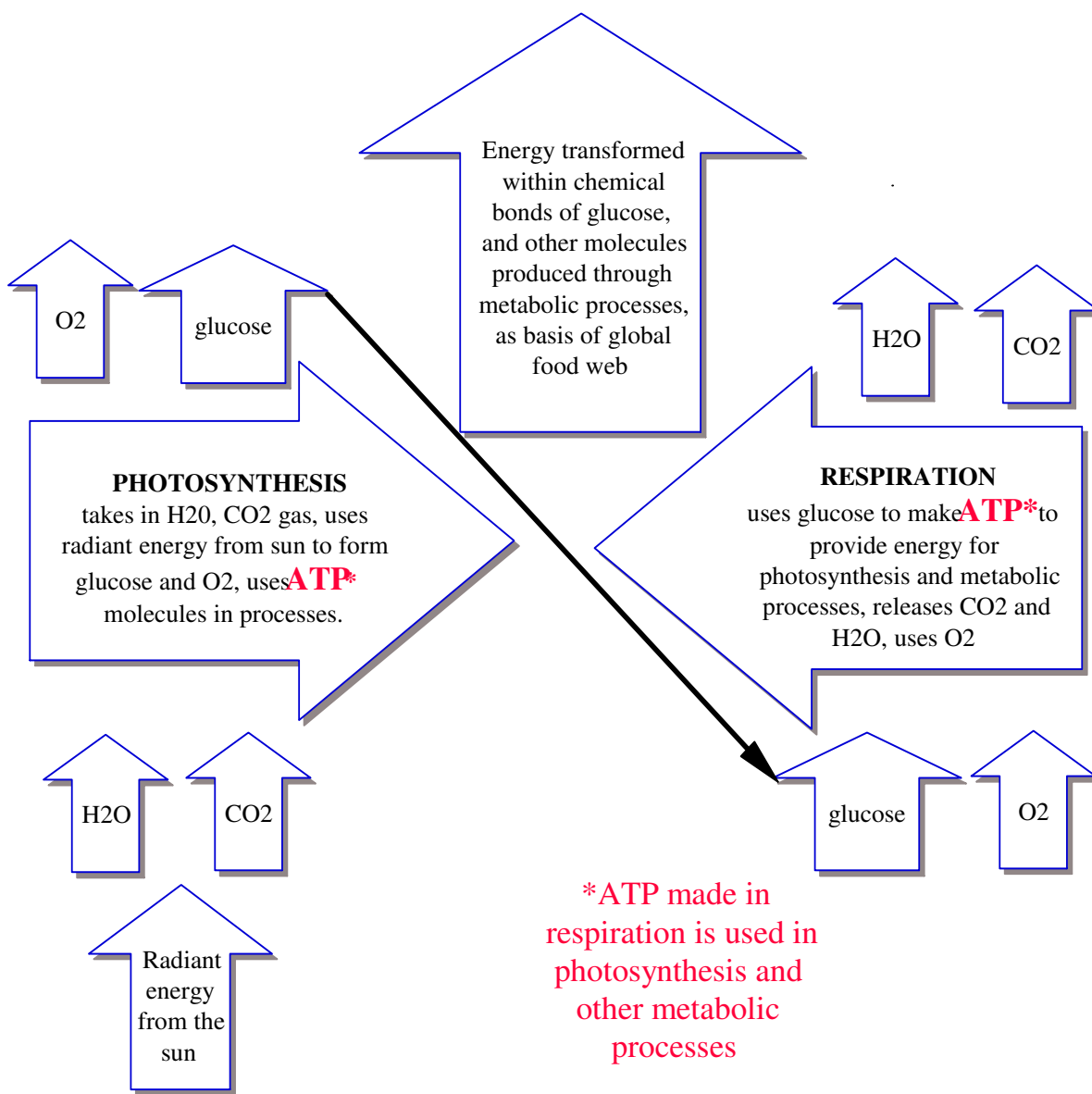


Figure 3: Research Design

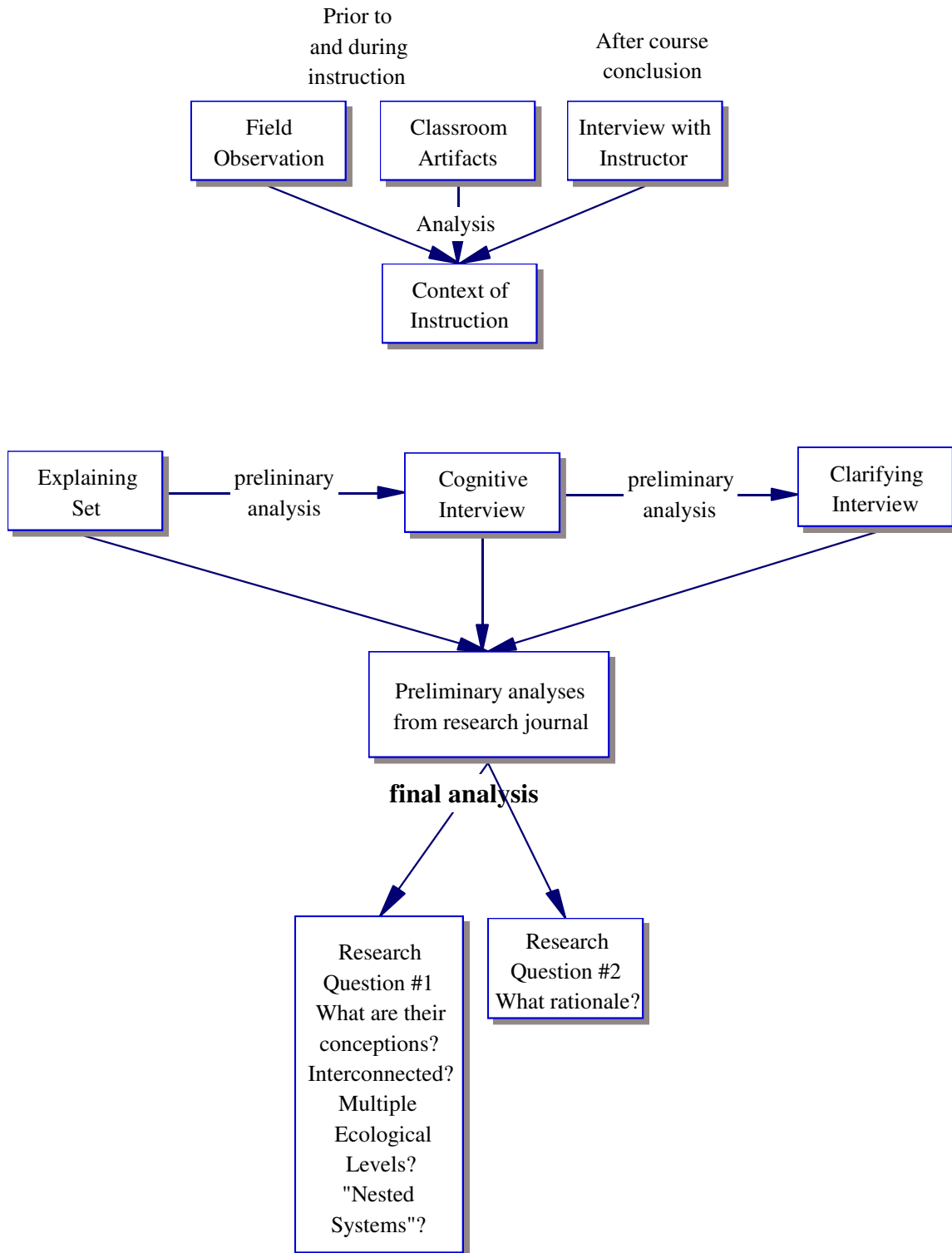
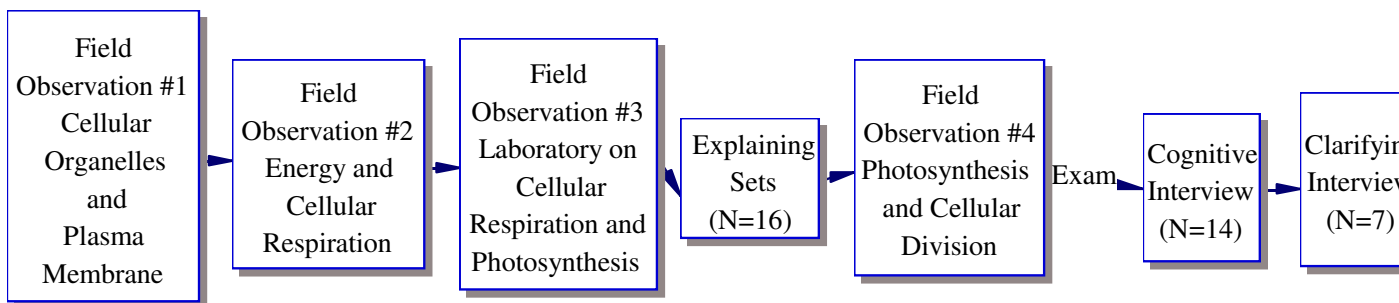


Figure 4: Time Line of Design

For Peer Review

Table 1: Participants on Multiple Levels

(Shaded areas represent participant focus on a specific level)

Participants	Global Level	Ecosystem Level	Organism Level	Cellular Level	Biochemical Level
Ann	Shaded	Shaded	Shaded	Shaded	Shaded
Bob	Shaded	Shaded	Shaded	Shaded	Shaded
Charles	Shaded	Shaded	Shaded	Shaded	Shaded
Nan	Shaded	Shaded	Shaded	Shaded	Shaded
Betty	Shaded	Shaded	Shaded	Shaded	Shaded
Jay	Shaded	Shaded	Shaded	Shaded	Shaded
Ken	Shaded	Shaded	Shaded	Shaded	Shaded
Amy	Shaded	White	Shaded	Shaded	Shaded
Anita	Shaded	White	Shaded	Shaded	Shaded
Carl	White	Shaded	Shaded	Shaded	Shaded
Joy	White	White	Shaded	Shaded	Shaded
Ruby	White	Shaded	Shaded	Shaded	Shaded
Shirley	Shaded	White	Shaded	Shaded	Shaded
Vera	Shaded	White	Shaded	Shaded	Shaded
Kay	Shaded	White	Shaded	Shaded	Shaded
Suzy	White	White	White	White	White
Totals	10/18 or 55.5%	10/18 or 55.5%	15/18 or 83.3%	4/18 or 22.2%	7/18 or 38.8%

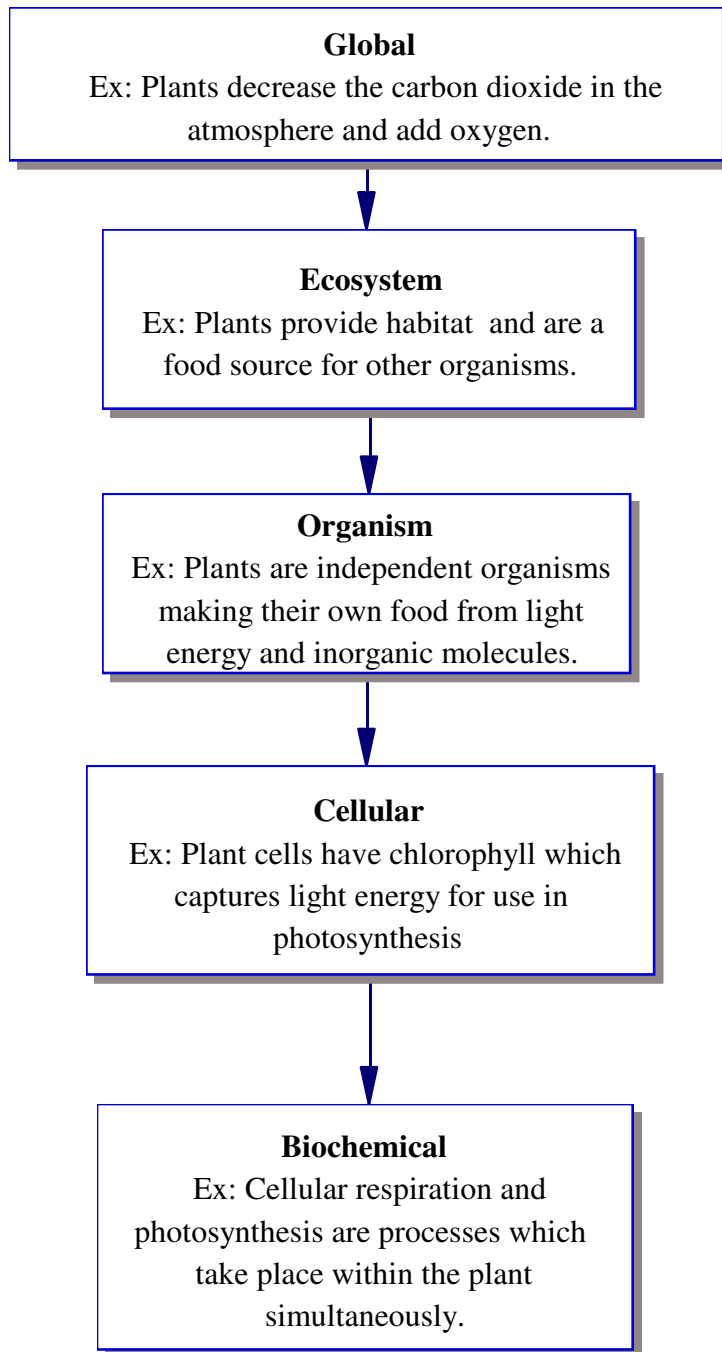
Figure 5: Ideal Explanation on Multiple Levels

Figure 6: Ann's Meta-Representation

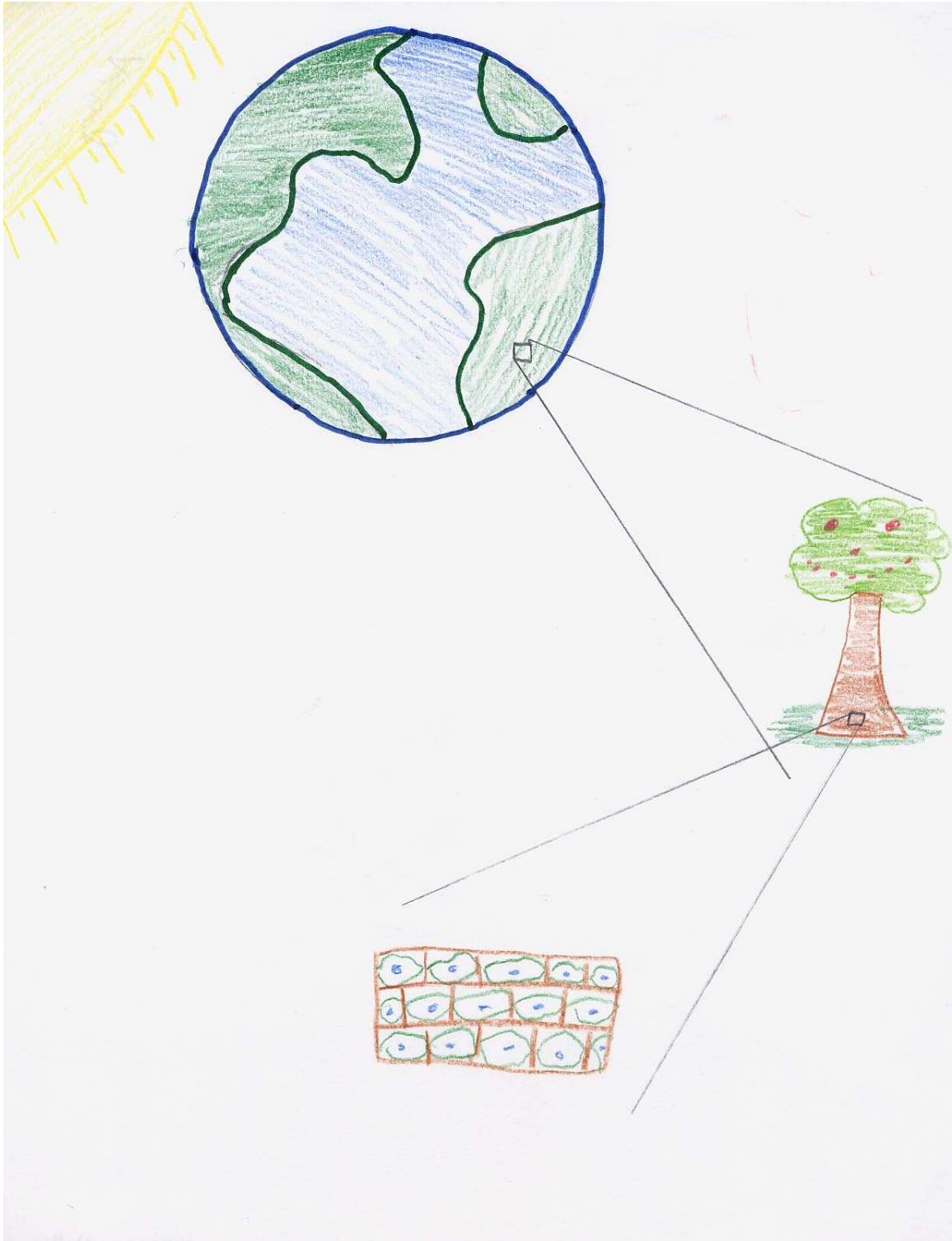


Figure 7: Model of the Pre-Service Teachers' Conceptions