US-China Education Review A 2 (2012) 183-198
Earlier title: US-China Education Review, ISSN 1548-6613

Secondary Students' Accounts of Carbon-Transforming Processes Before and After Instruction[*]

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The purpose of this study is to examine the extent to which more targeted instruction is helpful in eliciting students' scientific explanations of six selected carbon-transforming processes of combustion, cross processes, decomposition, growth, photosynthesis and respiration. We also examined these students' accounts regarding the corresponding principles of energy and matter. Students' accounts came from four secondary school teachers, two of whom used designed instructional materials and two did not. We first used grounded theory to analyze students' responses to pre-posttests regarding the six carbon-transforming processes. Then, we used matched-pair *t*-test to analyze these responses. We found overall significant pre-post gains in students' accounts in processes and principles among teachers who used more targeted instruction than those who did not. This was true even among teachers whose students' pretests were roughly similar. We also found no significant pre-post gains in high school students' accounts in the process of growth irrespective of form of instruction. Implications for research, science teaching and learning are discussed.

Keywords: matter, energy, carbon-transformation, pre-post, learning progressions

Introduction

Teaching for deeper understanding of natural phenomena has characterized reform-based science education standards (e.g., American Association for the Advancement of Science, 1993; National Science Education Standards, 1996). In line with these standards, there have been reform efforts especially in the last decade (Chin & Osborne, 2010). For example, there has been emphasis on scientific inquiry to improve student science learning. Such emphasis is important, because it challenges the science education community to transform instructional, and therefore, student science learning experiences in the classroom and beyond (Singer, Marx, & Krajcik, 2000). In

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[*] **Acknowledgements and Disclaimer:** The authors would like to thank several people for their invaluable contributions to the work presented in this paper. They would like to acknowledge the contributions made by Jing Chen, Li Zhan, Hamin Baek, Jonathon Schramm, Jennifer Doherty, Amy Lark, Dante Cisterna, Jenny Dauer, and Jiwon Kim, Michigan State University; Hui Jin, The Ohio State University in helping with data collection and qualitative analysis; Karen Draney, Mark Wilson, Yong-Sang Lee, and Jinnie Choi, at the University of California, Berkeley in helping with quantitative data analysis; and RET's: Marcia Angle, Lawton Schools, Rebecca Drayton, Gobles Schools, Cheryl Hach, Kalamazoo Math and Science Center, Liz Ratashak, Vicksburg Schools.

This research is supported in part by grants from the National science foundation: Learning progression on carbon-transforming processes in Socio-Ecological Systems (NSF-0815993), and Targeted Partnership: Culturally relevant ecology, learning progressions and environmental literacy (NSF-0832173), and CCE: A learning progression-based system for promoting understanding of carbon-transforming processes (DRL 1020187). Additional support comes from the Great Lakes Bioenergy Research Center. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation or the United States Department of Energy.

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response to reform-based science education, many new approaches are being utilized to drive deeper student scientific understanding of natural events in the world around them. The assumption behind the new approaches is that learners learn science better, when they are supported to gain scientific knowledge (e.g., processes and ideas) and skills (e.g., observations, data collection, analysis and presentation) over time.

To meet the reform agenda, as Marx, Freeman, Krajcik, and Blumenfeld (1998) and Singer et al. (2000) have argued, there is a need for science education stakeholders to develop responsive research programs that address such reform aspects as curriculum materials, instruction, professional development and assessment. Development of such program requires iterative understanding of effective aspects through continuous assessment. As part of a larger multi-year study within our environmental science literacy project, this study reports our initial iterative work focused on supporting students in deeper understanding of carbon-transforming processes in socio-ecological systems. Our project is guided by LP (learning progressions) framework. The NRC (National Research Council, 1996; Pophram, 2007; Smith, Wiser, Anderson, & Krajcik, 2006) describes learning progressions as sequenced and successively more complex ways of thinking about a topic that learners master and investigate over a broad span of time. This proposed model suggests that student reasoning about specific concepts is naive at school entry level, but progressively shifts to more complex reasoning through higher levels. As Mohan, Chen, and Anderson (2009) inform us, learning progressions are influenced by such societal expectations as science learning standards that span entry level, what we refer to as "lower anchor", to higher level, what we call "higher anchor".

Our goal in the larger project is to use iterative empirical data to support students to move towards deeper understanding of not only macroscopic events, but also microscopic events of natural processes including those of carbon-transformation. In line with reform-based science advocated for in the NSES (National Science Education Standards, 1996), our hope is to prepare students for (or at least move toward) participating in environmental decision-making (Mohan et al., 2009). While it is important that students are supported to move towards principle-based reasoning of events, visible or otherwise, it is equally important that teachers rethink and use empirically driven instructional approaches that help them to achieve this goal. We see a possibility in achieving this goal in the utilization of more targeted instruction. This can be done through, for instance, use of well designed instructional materials to help bridge complex systems in ways that make student learning possible.

Recent studies, on the one hand, have shown that more targeted instruction have led to improved student learning. To illustrate, Taylor, Van Scotter, and Coulson (2007, p. 44) have argued that curriculum development "has resulted in extensive portfolio of research-based instructional materials that span the sciences disciplines". Moreover, these studies have shown that instructional materials are useful in student science learning. For instance, a study by McNeill, Lizotte, Krajcik, and Marx (2006) revealed that instructional materials (fading written scaffolds) helped students write stronger scientific explanations on the basis of claim, evidence and reasoning. Additionally, more targeted inquiry-based science curricular has been shown to increase students' scientific knowledge and skills (Geier et al., 2008).

On the other hand, other studies have reported that students' atomic-molecular level scientific reasoning is still problematic. This is particularly true in explanations relating to carbon-transforming processes, especially at stages involving chemical changes (Cokelez, Dumon, & Taber, 2008; Hesse & Anderson, 1992). In particular, students find it hard to trace matter and/or energy separately in systems containing organic carbon at the atomic-molecular level, often confusing matter transformation with conversion of energy (Mohan et al., 2009). We hoped that by having teachers engage in more targeted instructions using designed instructional materials in supporting students in science learning activities, students will begin and/or continue to use scientific accounts necessary for participating in informed environmental decision-making now and in the future.

The Purpose of the Study

The purpose of this study is to examine the extent to which more targeted instruction is suited for supporting learners in developing deeper understanding of carbon-generating processes. These processes include: photosynthesis, biosynthesis, digestion and food chains and carbon-oxidizing processes through cellular respiration and combustion (Mohan et al., 2009). Specifically, we investigate the extent to which more targeted instruction using our instructional materials are helpful in eliciting students' scientific explanations of carbon-generating, carbon-transforming and carbon-oxidizing processes. We explore this through analyzing secondary school students' responses to items relating to these processes. Prior to intervention, students were first asked to respond to identified structured items about these processes. Then, during their regular class schedules, two teacher participants used designed instructional materials to purposely help students move towards constructing scientific explanations of carbon-transforming processes.

Research Questions

This study is guided by the following research questions:

(1) How do students' accounts of carbon-transforming processes in socio-ecological systems change as a result of instruction?

(2) How are changes in students' accounts of carbon-transforming principles related to differences in instruction?

These questions were studied during a learning progression investigation about student learning in regularly scheduled classes during the spring semester of 2008.

Methods

Participants and Context

We followed 227 middle and 151 high school students in one- to two- month long LP intervention from secondary schools near a large Midwestern city, as they were taught using the aforementioned instructional materials. Whereas there were five secondary school teacher participants in the study, we selected four, because they had most of their students' complete pre-/post- tests. Three of these teachers and their students attended public schools, and one and her students attended a math and science center for gifted high school students. Her students, however, returned to their public schools for other courses. The selected teachers and students mainly came from school districts with a largely higher Caucasian student population (approximately 88%). An average 37% of the students received either free or reduced lunch.

Student participants completed a short pre-test on a number of structured items relating to carbon-generation, transformation and oxidation processes. Depending on class schedules, the start of the intervention varied from school to school. Using these items, we sought students' reasoning about these processes. For example, we asked students to explain: What happens to matter when a person loses weight (use substances and chemical processes in your response); Why people use gasoline instead of water to run their cars; and What happens to matter ("stuff") of gasoline when the car uses it to run. Two of the four secondary school teachers used the designed instructional materials to support their students work towards constructing scientific explanations of what happens to carbon during the aforementioned natural processes. The remaining two teachers did not use our instructional materials (i.e., used traditional instruction). After an average of one- to two- month long intervention, student participants completed a short post-test on the same pre-test questions.

Data Analysis

The pre-/post- tests were analyzed using exemplar workbooks that we developed based on the quality of sampled student item responses and level of achievement. We provide examples of student responses and a description of levels of achievement showed in Table 1. The development of this workbook was gradual. During the first round of blind coding of transcribed student responses, four research team coders agreed over 80% of the time with disagreements settled on consensus. Next, we identified emerging patterns which we then used to develop levels of achievement. For student accounts characterized by materials as enablers, we designated them as level 1, and those characterized by chemical processes with conservation of atoms and molecules, we designated them as level 4. For the second and third round coding, we followed round one procedure but with subsequent larger samples of student responses. The final coder agreement was over 90%.

Table 1

Level of Achievement and Sample Student Item (Body Temp) Responses

Level	Body temp characteristics of responses	Exemplar responses
4. Agency at atomic/molecular scale—atom rearrangement associated with energy transformation and degradation—successfully use energy transformation and degradation as constraints on processes.	Identify the major source of body heat as food/organic molecules and understand heat as unavailable energy form, or identify chemical changes. Using energy degradation to constrain chemical changes.	The author thinks that this is right because when we take in food only 10% is used as energy and the rest gets used up as heat.
3. Agency at cellular level (unsuccessful constraints)—unsuccessfully use matter/ energy as constraints of processes.	Recognize food or organic substances in food as the major source of energy for body temperature and attempt to trace energy, but do not recognize heat as the energy form different from usable form of energy and/or cannot trace energy separately from matter, or, identify changes of matter/energy happened to foods when eaten by people. Unsuccessful constrain chemical changes.	c. heat mainly comes from the food we eat. Explanation: We actually break down the nutrients to get energy. For example, we break down carbohydrates and protein to get energy.
2. Agency at organ level (hidden mechanism)—energy as enabler: (1) associate foods, fuels, sunlight, warmth with energy; and/or (2) view energy as enabler of processes.	(1) May recognize that food provide heat for human body, but do not trace energy in processes; (2) Do not identify food as the major energy source for body temperature: May identify heat transfer from the sun. May hold the idea that heat/energy is created when doing exercises: Heat/energy/foods as enabler of body temperature.	c. heat mainly comes from the food we eat. Explanation: When you eat, the food creates energy and when you burn the energy through activeness and exercise, your bodies thermal energy and heat go higher. d. When people exercise their bodies create heat because they are moving around.
1. Agency at organism scale (force-dynamics causation)—multiple macroscopic enablers of events.	Attribute body temperature to external factors such as wearing clothes: External factors as enablers of body temperature.	b. If your clothes that you are wearing are sweats, they will keep you really warm. The clothes create heat while your body is in them.

Following coding of all students' responses, we used matched pair t-test to examine the overall effect of more targeted instruction on students' accounts of carbon-transforming processes. In particular, and based on pre-post item responses, we examined overall changes in students' accounts of: (1) carbon-transforming processes as a result of instruction; (2) regarding the principles of matter and energy; and (3) by instruction and grade level. In total, we examined students' responses to items relating to six carbon-transforming processes of combustion, cross processes, decomposition, growth, photosynthesis and respiration.

Findings

Our analysis of sampled student item responses showed, overall, that whereas traditional instruction produces marginal changes in students' levels of achievement in selected carbon-transforming processes, some more targeted forms of instruction show more promise. This pattern was found in our analysis of carbon-transforming: (1) processes by instruction; and (2) principles by instruction.

Changes in Students' Accounts of Carbon-Transforming Processes as a Result of Differences in Instruction

In using our exemplar workbooks to analyze the students' responses to items in the preceding six processes, we found more significant gains in pre-post accounts of these processes. These gains were, however, from students' responses whose teachers used more targeted instruction. We began our analysis by first examining overall pre-post comparisons between students whose teachers used more targeted instruction and those who did not in terms of processes by grade level and principles by grade level. Then, we examined specific processes by instruction.

Overall, our data analysis fell into recognizable patterns. For example, we noted a pattern of significant pre-post gains in processes and principles among students whose teachers used more targeted instruction than those students whose teachers used traditional instruction. Moreover, there was a notable pattern of no significant pre-post gains in the process of growth irrespective of the instructional approach used among high school students. These patterns were evident in both comparisons by grade level and comparisons by instruction in relation to the six processes and the corresponding principles we examined.

Table 2

Pre-post Comparison of Processes by Grade Level

Grade level		*t*-test for equality of means						
		t	*df*	Sig. (2-tailed)	Mean difference	Std. error difference	95% confidence interval of the difference	
							Lower	Upper
Middle	Comb	-2.267	225	*0.024*	-0.321	0.142	-0.600	-0.042
	Cross	0.249	225	**0.804**	0.033	0.134	-0.231	0.298
	Decom	-0.438	225	**0.662**	-0.071	0.163	-0.393	0.250
	Growth	-2.423	225	*0.016*	-0.335	0.138	-0.607	-0.062
	Photo	1.078	225	**0.282**	0.111	0.103	-0.092	0.315
	Resp	-1.763	225	**0.079**	-0.094	0.053	-0.200	0.011
High	Comb	-5.657	149	*0.000*	-1.415	0.250	-1.909	-0.920
	Cross	-3.862	149	*0.000*	-0.805	0.208	-1.217	-0.393
	Decom	-2.452	149	*0.015*	-0.814	0.332	-1.470	-0.158
	Growth	-0.021	149	**0.983**	-0.004	0.209	-0.417	0.408
	Photo	-3.596	149	*0.000*	-0.985	0.274	-1.526	-0.444
	Resp	-5.303	149	*0.000*	-0.639	0.120	-0.876	-0.401

Overall Comparisons of Processes by Grade Level and the Process of Growth

In looking at overall processes by grade level, we found higher pre-post gains in high school than in middle school (see Table 2 and Figure 1). Specifically, we noticed that in high school, there were positive gains in five out of the six processes we examined. We italicize these gains in Table 2 (see under Sig.). That is, we found that of the six processes we examined, only growth showed no pre-post gain $t_{(149)} = -0.021$, $p > 0.05$. By comparison, only two out of six processes in the middle school showed positive pre-post gains in students' accounts of carbon-transforming processes. We italicize these gains (in combustion and growth) and bold no significant gains (remaining processes) in Table 2. In addition to overall more targeted instruction looking more promising than traditional instruction, these results suggest that high school students struggle to understand carbon-transformation in the process of growth. As we will show in this paper, this pattern was observed among all high school teachers' irrespective of form of instruction.

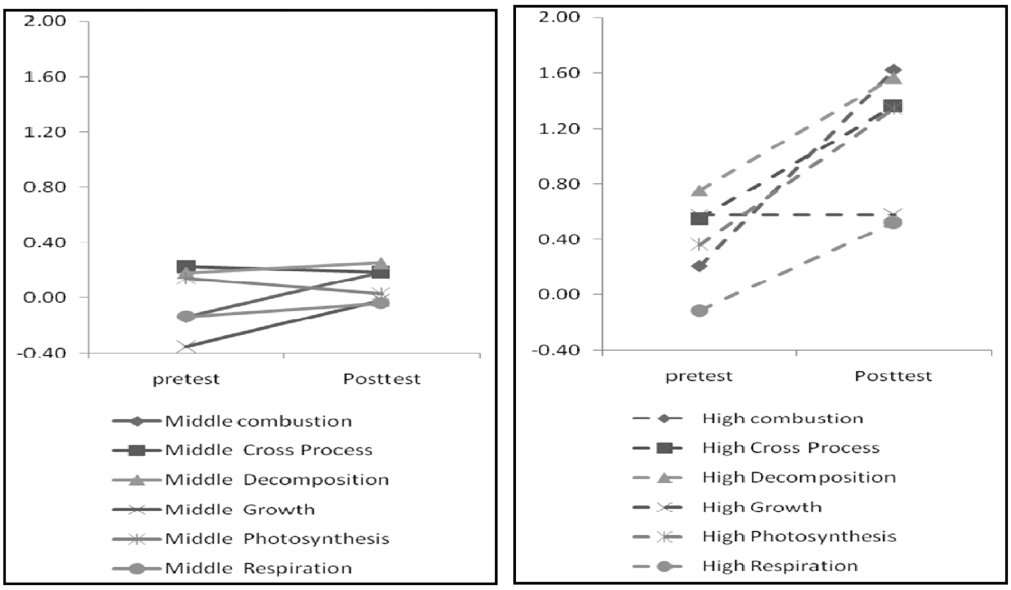

Figure 1. Graphical pre-/post- test comparison of processes by grade level.

Overall Comparisons of Principles by Grade Level

Our analysis of principles by grade level showed similar patterns of performance as process by grade level. That is, unlike middle school, we found pre-post gains for high school in the two principles of energy and matter. We italicize these in Table 3 (see Figure 2). Contrary to high school pre-post gains, middle school students' accounts showed no overall significant gain in either of the two principles of energy and matter (see bold in Table 3). On the one hand, our findings suggested that high school students perform better in their accounts of carbon-transforming processes than middle school students. This inference follows from the clear pattern of higher level overall performance by high school students in processes where pre-post gains were five out of six (or 83.3%) unlike middle school students' performance in processes where pre-post gains were in two out of the six (or 33.3%) processes considered. Additionally, improved pre-post performance in principles of energy and matter in high school, unlike middle school students who showed no significant pre-post gains in either of the two principles, suggests that high school students, overall, perform better than middle school students in carbon-transforming processes.

On the other hand, we reasoned that, for high school students, pre-post gains in some processes (e.g., photosynthesis) and not in others (e.g., growth) suggested that some items were more challenging than others. Similarly, some items (e.g., photosynthesis and respiration) may be more challenging for middle school students than others (e.g., combustion and growth). Given that our work is iterative in nature, these results led us to check for item quality and therefore validity regarding levels of achievement in especially the process of growth. But first, we analyzed specific processes by instruction and principles by instruction to determine if indeed some processes stood out.

Table 3

Pre-post Comparison of Principles by Grade Level

Grade level		*t*-test for equality of means						
		t	*df*	Sig. (2-tailed)	Mean difference	Std. error difference	95% confidence interval of the difference	
							Lower	Upper
Middle	Energy	-1.889	225	**0.060**	-0.149	0.079	-0.304	0.006
	Matter	-1.077	225	**0.283**	-0.104	0.097	-0.294	0.086
High	Energy	-5.627	149	*0.000*	-0.842	0.150	-1.138	-0.547
	Matter	-3.814	149	*0.000*	-0.723	0.190	-1.098	-0.348

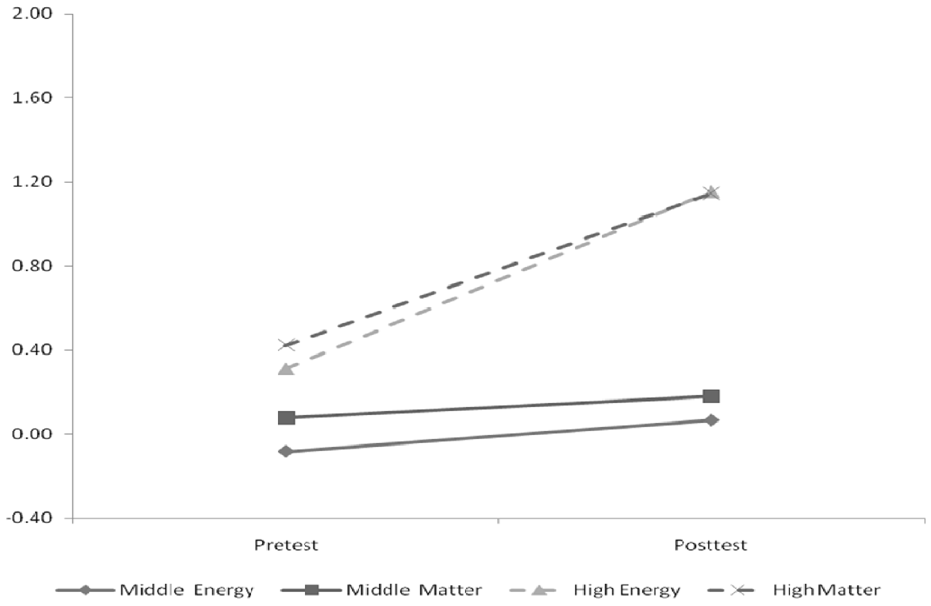

Figure 2. Graphical pre-/post- test comparison of principles by grade level.

Comparisons of Specific Processes by Instruction

Specific pre-post gains and the process of growth. In terms of specific processes by instruction, we found, on the one hand, that there were higher pre-post gains among students whose teachers (Holy and Randi) used more targeted instruction (see Table 4 and Figure 3). Specifically, in addition to showing marginal gains in photosynthesis, Holy's students' accounts showed significant gains in four out of the six carbon-transforming processes we examined. These gains were in combustion, cross processes, decomposition and respiration. However, the same students' accounts did not show gains in the process of growth. We italicize significant pre-post gains and those with no pre-post significant gains in bold (see Table 4). Similarly, Randi's students' accounts showed significant gains in four out of the six carbon-transforming processes. These were in combustion, cross processes, photosynthesis and respiration. Randi's students' accounts, however, did not show significant gains in decomposition, and like Holy, in the process of growth.

On the other hand, we found little significant pre-post gains in students' accounts of carbon-transforming processes among teachers (Amanda and Macy) who used traditional instruction (see Table 4 and Figure 3). Specifically, Amanda's students' accounts showed mixed results with pre-post gains in three processes (i.e., decomposition, respiration and photosynthesis). At the same time, Amanda's students' accounts showed no significant pre-post gains in the processes of combustion, cross processes and growth (see Table 4). Similarly, Macy's students' accounts did not show significant pre-post gains in four out of the six processes (i.e., photosynthesis, cross processes, respiration and decomposition). Again, for significant gains from students' carbon-transforming accounts, we italicize them and for accounts that did not show significant gains we bold them (see Table 4). The overall mixed results here are suggestive of a pattern: That students tend to make progress in their accounts of carbon-transforming processes over time. However, this progress is not significant enough to encourage traditional instructional approaches.

Table 4

Pre-post Comparison of Processes by Instruction

Teacher ID		*t*	*df*	Sig. (2-tailed)	Mean difference	Std. error difference	95% confidence interval of the difference	
							Lower	Upper
MA	Comb	-2.267	225	*0.024*	-0.321	0.142	-0.600	-0.042
	Cross	0.249	225	**0.804**	0.033	0.134	-0.231	0.298
	Decomp	-0.438	225	**0.662**	-0.071	0.163	-0.393	0.250
	Growth	-2.423	225	*0.016*	-0.335	0.138	-0.607	-0.062
	Photo	1.078	225	**0.282**	0.111	0.103	-0.092	0.315
	Resp	-1.763	225	**0.079**	-0.094	0.053	-0.200	0.011
A	Comb	-0.834	35	**0.410**	-0.239	0.287	-0.823	0.344
	Cross	-0.622	35	**0.538**	-0.170	0.273	-0.723	0.384
	Decomp	-2.638	35	*0.012*	-0.914	0.347	-1.618	-0.211
	Growth	0.957	35	**0.345**	0.421	0.440	-0.472	1.315
	Photo	-2.527	35	*0.016*	-0.913	0.361	-1.647	-0.180
	Resp	-3.049	35	*0.004*	-0.414	0.136	-0.690	-0.138
H	Comb	-6.410	68	*0.000*	-2.095	0.327	-2.747	-1.443
	Cross	-3.538	68	*0.001*	-1.029	0.291	-1.609	-0.448
	Decomp	-1.994	68	*0.050*	-0.855	0.429	-1.711	0.001
	Growth	-0.546	68	**0.587**	-0.143	0.261	-0.664	0.378
	Photo	-1.934	68	0.057	-0.715	0.370	-1.452	0.023
	Resp	-4.738	68	*0.000*	-0.831	0.175	-1.181	-0.481
R	Comb	-3.327	42	*0.002*	-1.118	0.336	-1.796	-0.440
	Cross	-2.810	42	*0.007*	-0.858	0.305	-1.475	-0.242
	Decomp	-0.841	42	**0.405**	-0.410	0.487	-1.394	0.574
	Growth	-0.139	42	**0.890**	-0.048	0.346	-0.747	0.650
	Photo	-3.247	42	*0.002*	-1.289	0.397	-2.090	-0.488
	Resp	-2.113	42	*0.041*	-0.440	0.208	-0.859	-0.020

Comparisons among teachers with similar pre-tests and the process of growth. We further analyzed data from teachers whose students' pre-test accounts were roughly similar (see Figure 3). When we looked at high school only, we found similar results as we did in "specific pre-post gains and the process of growth" above. Whereas Amanda, who had not used more targeted instruction, had pre-post gains in three processes, teachers Holy and Randi, who had used more targeted instruction, showed positive gains in four processes each. Again, growth was among processes in which students' pre-post accounts showed no significant gains. We also compared students' pre-post accounts from Amanda and Randi. These were high school teachers whose students' pre-tests were nearly similar in the sense that these teachers' students started nearly at the same pre-test level (see Figure 3). Our findings once again showed that students' accounts from Randi who had used more targeted instruction showed more pre-post gains (four out of six) than did students' accounts from Amanda who used more traditional instruction (three out of six). Again, growth showed no significant pre-/post- test gains from either of the two teachers' students' accounts.

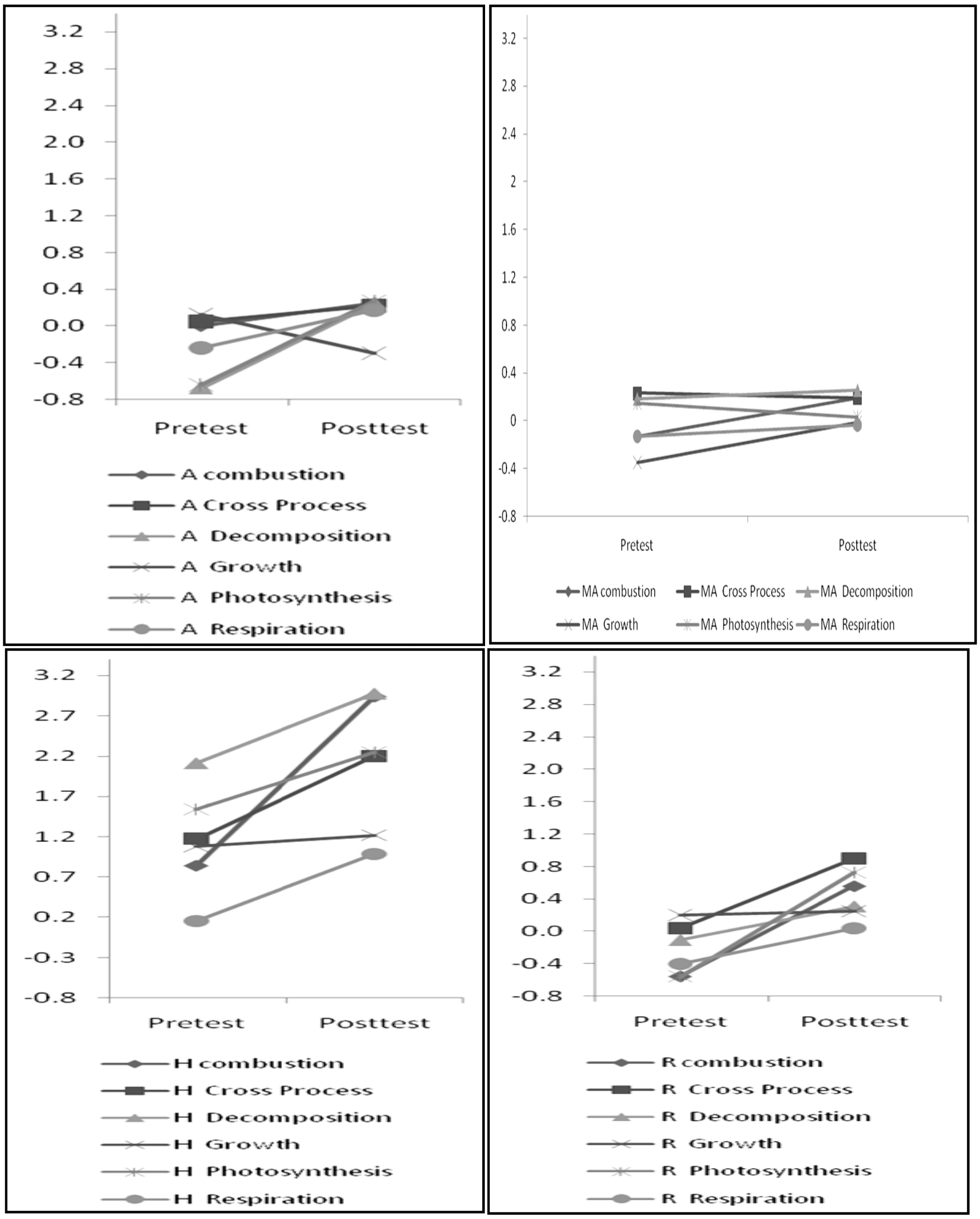

Figure 3. Graphical pre-post comparison of processes by instruction.

When we looked at middle school, we found comparable results. Macy, like Amanda from high school, had not used more targeted instruction in her class. Although Macy's students' pre-test scores were roughly similar to those of Amanda's and Randi's students (see Figure 3), yet, our analysis showed that her students' accounts showed positive gains in only two (combustion and growth) out of the six processes. We interpreted this to mean that middle school students generally perform better in these two processes than other processes. Moreover, given that only middle school students' accounts in the process of growth showed significant pre-post gains, we wondered if this process well aligned to other processes at the high school. This suggests that more work is needed to show the effects of curricular alignment on students' understanding of carbon-transforming processes. We also reasoned that lack of significant improvement in the process of growth among high school students could be due to the growth item validity at that level. We thus checked for this item's validity.

Item validity and the process of growth. After confirming that high school students' pre-post carbon-transforming accounts showed no significant gains irrespective of form of instruction, we qualitatively checked for these items' validity. To do this, we began with the assumption that if the items we used were valid, then they could elicit responses at all levels of achievement. To find out if this was the case, we first checked our earlier validity estimates of growth items (see underline in Appendix A). Then, we checked our exemplar worksheets (see example in Appendix B).

Our validity estimates (see Appendix A) showed that all but two items were valid at levels 1 through 4. The two invalid items were; ENERPEOP (energy people) invalid at level 4, and STOREEN (store energy) invalid at level 1. Whereas this may be true, other items seemed to be invalid at level 4, because they did not generate students' accounts of carbon-transforming process of growth at that level (see Appendix B). These items included INFANT (infant growth) and EATAPPLE (eat apple). We also noted that the item "lighten" was structured differently for middle school than it was for high school. Additionally, STOREEN (store energy) was designed for high school only. From these observations, we hypothesized that most items in the process of growth for high school were not adequate enough for examining students' pre-post accounts of this process. We think that further future work relating to these and similar items may help us improve our approaches to assessment of carbon-transforming processes among high school students.

Comparisons of Principles by Instruction

Overall, on the one hand, there were pre-post gains in students' accounts regarding principles among teachers who used targeted instruction (see Table 5 and Figure 4). We italicize significant gains in Table 5. Specifically, Holy's pre-post students' accounts of carbon-transforming processes relating to both the principles of energy and matter showed significant positive change.

Similarly, Randi's students' accounts showed significant gains in the pre-post tests in their accounts regarding both the principles of energy and matter. On the other hand, overall, we found little significant pre-post gains in students' accounts regarding principles among teachers who used traditional instruction (see Table 5 and Figure 4). That is, whereas Amanda's students' accounts showed pre-post gains in the principle of matter, these students' accounts did not show significant pre-post gains in the principle of energy. We italicize pre-post gains and bold those with no pre-post gains in Table 5.

Contrary to Holy's and Randi's students' pre-post significant gains in both the principles of energy and matter, Macy's students' pre-post tests showed no significant change in either of the two principles (see Table 5). Given that both Holy and Randi, unlike Amanda and Macy, were the only teachers who used more targeted instruction, we, although cautiously, think that more targeted instruction matter in supporting students to develop deeper understandings about natural phenomena, in this case carbon-transforming processes.

Table 5

Pre-post Comparison of Principles by Instruction

Teacher ID		*t*	*df*	Sig. (2-tailed)	Mean difference	Std. error difference	95% confidence interval of the difference	
							Lower	Upper
MA	Energy	-1.889	225	**0.060**	-0.149	0.079	-0.304	0.006
	Matter	-1.077	225	**0.283**	-0.104	0.097	-0.294	0.086
A	Energy	-1.413	35	**0.166**	-0.319	0.226	-0.777	0.139
	Matter	-2.761	35	*0.009*	-0.568	0.206	-0.986	-0.151
H	Energy	-6.811	68	*0.000*	-1.094	0.161	-1.414	-0.773
	Matter	-3.940	68	*0.000*	-0.741	0.188	-1.117	-0.366
R	Energy	-4.254	42	*0.000*	-0.770	0.181	-1.135	-0.405
	Matter	-2.940	42	*0.005*	-0.631	0.215	-1.064	-0.198

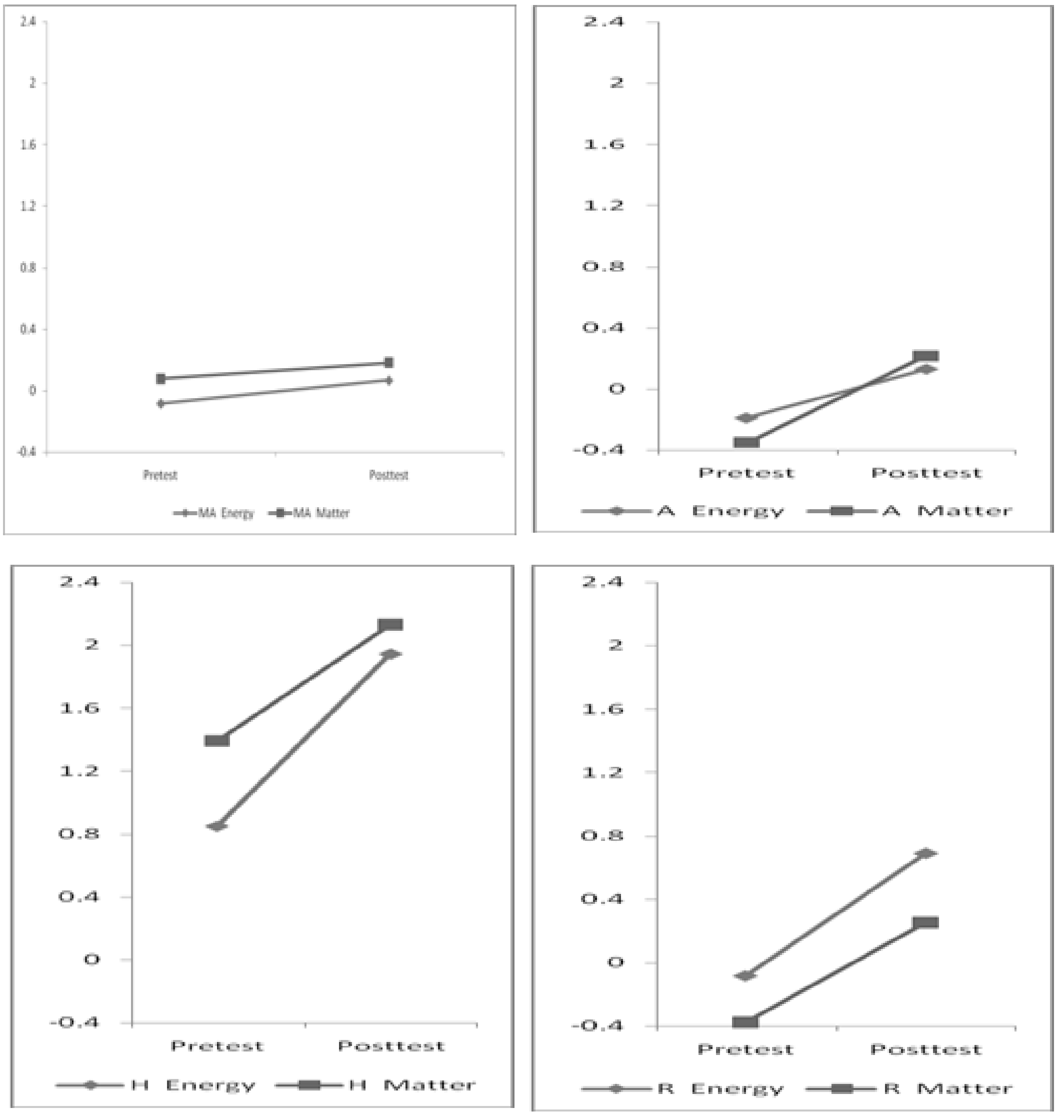

Figure 4. Graphical pre-/post- test comparison of principles by instruction.

Discussion: Limitation and Implications

Limitation

In this study, we examined changes in students' accounts of carbon-transforming processes in socio-ecological systems before and after instruction and how this related to differences in instruction. This was based on data from about 227 middle school students and about 151 high school (nine to 12 grade) students in one- to two- month long learning progressions interventions using the aforementioned instructional materials. Before we proceed with the discussion on design, results, implications, and so on, we wish to note that one of this study's limitations relates to its design: That we did not include data about how specifically, with or without instructional materials, each of the four teachers included here engaged their students in learning about carbon-transforming processes. However, building off this study is another study (Zhan et al., in progress) from the environmental science literacy project. Zhan et al.'s study examines effects of teaching materials and teachers' instructional approaches to learning about carbon-transforming processes. Preliminary findings indicate that teaching materials have a significant influence on student learning. In other words, although we were interested in pre-post-tests, we were unable to specify how targeted instruction specifically related to the changes we identified. This was because we knew little about the specific instruction students received. We were particularly interested in documenting the development of students' accounts rather than what caused it.

We now return to the point about design and results. We intentionally allowed participant teachers to follow their instructional schedules to avoid unintended distractions. For example, rather than completely abandon teachers' curricular units, we build our units around them. By allowing more targeted instruction to be used by a pair of teachers and traditional instruction by another pair, we feel that we successfully set up a control in a regular instructional setting. As Samarapungavan, Mantzicopoulos, and Patrick (2008) have noted, the comparison group provided baseline data for examining secondary students' accounts about carbon-transforming processes.

Implications

Students' responses from these pairs of teachers showed distinct patterns in the categories of principles by grade level, processes by grade level and principles by instruction. Overall, compared to students' responses whose teachers used traditional instruction, students' responses whose teachers used more targeted instruction showed significant pre-post gains in nearly all the categories we considered. Given that only students' responses from teachers Holy and Randi showed significant pre-post learning gains, this suggests that more targeted instruction played an important role in student learning of the fundamental science concepts of matter and energy we focused on. These results are suggestive: That more similar and longitudinal future studies need to be done, especially in more diverse contexts, to assess the universality of application of our findings.

Although not all students will follow a general sequence of development (Duschl, Schweingruber, & Shouse, 2007), our findings suggest a general trend of a learning progression of some kind. This is evidenced by not only overall higher pre-post gains but also in the two principles of matter and energy in high school than middle school groups (see Tables 2 and 3, Figures 1 and 2). Whether this trend is true for similar interventions in different content areas and more diverse contexts remains a question for a likely future study. Our analysis of pre-post by instruction revealed a similar pattern: That, students' responses from teachers who used more targeted instruction generated overall significant gains. We cautiously think that this development has to do with the mode of instruction used. Moreover, at high school level, we found no gains in the process of growth irrespective of mode of instruction. Our further analysis suggests more research to examine item validity (i.e., quantitative), and/or students' accounts regarding the process of growth.

As we noted earlier, this study is a part of other studies (Mohan et al., 2009; Covitt, Tan, Tsurusaki, & Anderson, 2009; Gunckel, Covitt, & Anderson, 2009) on environmental literacy that are focused on iteratively refining a LP framework. As Mohan et al. (2009) pointed out, this framework began by documenting the current reality about how students' reasoning changes without any instructional interventions. What has emerged over the years is an empirically grounded LP framework with four levels of achievement described earlier (see Table 1). Products of this work include other papers (Mohan et al., 2009) suggesting that only 10 % of high school students' reasoning tends to fall at level 4. Our current work includes pilot instructional interventions aimed at supporting students to move towards level 4 reasoning. Unlike other studies in the larger project, this study has documented changes in students' accounts as a result of more targeted instruction. Thus, with one of our end goal of providing important frameworks for research in mind, this study contributes to our iterative work on the development of empirical validation of learning and assessment.

Furthermore, level 4 reasoning points to knowledge and skills necessary for environmentally literate citizenry among students. We believe that such level of reasoning is important in a knowledge economy where high school graduates are expected to responsibly participate. For example, as responsible citizens, they are expected to advance evidence-based arguments on environmental issues, such as global climate change. Yet, our previous work shows that only one tenth of such graduates can knowledgeably engage in environmental issues. Our current study implies that sustained intervention in curriculum development and teacher support is critical in helping students to move towards constructing scientific accounts of natural phenomena—a shift from force-dynamic to more model-based reasoning (Pinker, 2007). Thus, this study can potentially inform science education research in terms of development of curriculum materials, instruction and assessment for improved student learning as well as teacher professional development (NRC, 2007). Specifically, results from this study offer a glimpse into what is possible in developing students' understanding of fundamental scientific ideas of matter and energy.

In sum, we have build on the idea that learners constantly encounter a multiplicity of challenges regarding deeper and connected science learning of the natural world. Work on supporting learners to meaningfully learn science has been the basis for the constant call for reform-based science teaching (AAAS (American Association for the Advancement of Science), 1993; NRC, 2007). This is consistent with other calls for investments in research on instruction and learning (National Science Board, 2006). This study is one of our attempts to respond to calls for reform-based instruction and learning. In spite of the limitations identified earlier (e.g., lack of data triangulation), we think that the results we have reported here will provide a basis for interesting future studies. We also think that the current study will not only be a reference point for instructional practice, but also a reference point significant enough for discussion among the science community of practice.

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Appendix A

Table A1

Item Validity Estimates

Item	Grade level	Validity estimates				
		Level 1	Level 2	Level 3	Level 4	Invalid for:
AIRDIFF	EMH					
ANIMWNTR	E				▨	E & M
APPLEROT	EMH					
BODYTEMP	EMH				▨	M & E
BRNMATCH	E					
CUTTREE	E					
DEERWOLV	H					
DIFEVENTS	EMH				▨	M & E
EATAPPLE	EMH					
ECOSPHERE	MH					
ENERPEOP	MH				▨	M & E
ENERPLNT	MH					
ENPYRAMID	H					
FDFINGER	E				▨	M & E
GAS_MT	MH					
GASWATER	EMH					
GLUGRAPE	MH	▨				M & E
GRANJOHN	MH	▨				M
HOTTHINGS	MH				▨	E
INFANT	EMH					
JARED	E				▨	M & E
LBULB	MH	▨				E
LIGHTENELM	E				▨	E
LIGHTENMID	M					
LIGHTENHI	H					
SEEDGAIN	H					
STOREEN	MH	▨				E
THINGTREE	EMH					
TREEDECAY	EMH					
TROPRAIN	MH	▨				M & E
WAXBURN	EMH					
WOODMIX	EMH					
WTLOSS	EMH					

Notes. E = Elementary; M = Middle; and H = High school; Grey highlight = "invalid for (grade level) at (level)" e.g., BODYTEMP is invalid for E & M at level 4.

Appendix B

Table B1

Exemplar of Growth Items Worksheet

Level	Characteristics/description of transformation items	MUSCMIX	
		Characteristics of responses	Exemplar responses
4. Chemical processes with conservations of atoms and mass.	Explain digestion and biosynthesis at the atomic-molecular and cellular levels, focusing on key reactants and products. Recognize that growth of organisms occur when organisms synthesize simple carbohydrates and amino acids into more complex molecules (lipids, proteins, etc.).	Identify muscle cell in terms of atomic-molecular scale and identify chemical substances in the cell.	I believe that the muscle cell is made up of many different things, like lactic acid when you are lifting things or using the muscle, glucose is stored in the cell in order for the cell to have enough energy, it is made up of tissues that come together to form the muscle.
3. Materials as transformed by processes with matter-energy conversion, no conservation of atoms.	Identifies important chemical substances that are obtained from eating food and trace these to cellular level with a cellular mechanism for matter transformation during digestion.	Recognize components of muscle (carbon based minerals) at cellular level.	Muscle cells contain different elements and minerals that are carbon-based, but the source of those compounds is varied and composed of many substances that used the matter previously. Muscle cells have different parts in them, like cytoplasm, mitochondria, cell wall, cell membrane, nucleus etc.. They are animal cells and are made up of different parts.
2. Materials as enablers with solid-solid and gas-gas cycle.	Recognize that food or other materials are incorporated into the body and transformed by organs for the body to use. Do not consistently distinguish matter from other conditions such as sunlight and exercise. Air is not consistently recognized as matter that can contribute to mass increase.	Identify muscle as mixture, but do not name any components of muscle.	There of course would be several elements in the muscle cell, but I think there would have to be several different structures made form different things to complete the cells job.
1. Materials as enablers.	Focus on natural tendency of food and other materials to help gain weight. Explain in terms of human intentions or experiences. Does not recognize that food contains energy-rich materials or is transformed into the body (does not mention organs involved in digestion).	Explain muscle based on human intentions, and do not identify mixture.	Muscle cells make people strong to lift things up.