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Teaching Complex Concepts in the Geosciences by Integrating Analytical Reasoning With GIS

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ABSTRACT

Conceptual models have long served as a means for physical geographers to organize their understanding of feedback mechanisms and complex systems. Analytical reasoning provides undergraduate students with an opportunity to develop conceptual models based upon their understanding of surface processes and environmental conditions. This study describes the use of analytical reasoning by junior and senior undergraduate students to predict the expansion and contraction of the South Texas Sandsheet as an example of this instructional technique. Students perceived that the analytical reasoning approach was significantly better for understanding desert expansion and contraction compared with the traditional lecture. A preliminary assessment of an analytical reasoning approach to desertification is presented as an example of how this approach can be incorporated into undergraduate geoscience courses. © *2017 National Association of Geoscience Teachers*. [DOI: 10.5408/16-152.1]

Key words: Geoscience instruction, geomorphology, aeolian processes, desertification, analytical reasoning, active learning

INTRODUCTION

Addressing global issues of resource availability, sustainability, and scientific and applied problem solving in our rapidly changing society will require a highly-educated workforce with scientific and technological literacy (Bishop, 2009). It is therefore important that undergraduate students are provided with effective training and high-impact learning experiences that facilitate critical thinking, creativity, and exploration, quantitative and computer skills, and multidisciplinary problem-solving experience (Bailey, 2000; Bishop, 2009). It is also important that the multidisciplinary treatment of knowledge from science, technology, engineering, and mathematics (STEM) disciplines is integrated and disseminated in innovative ways to address the complexity of subject material and facilitate effective and reflective learning (Niess, 2005; Lou et al., 2011).

Learning from books and lectures alone limits the potential for self-discovery and the use of observations to discover the relationships and complexity of phenomena in the geosciences (Davis, 1887). Despite this early observation and numerous arguments in support of inquiry-based learning in the recent literature (e.g., Edelson et al., 1999; Groh, 2001; Williams, 2001; Duffy and Kirkley, 2004; Fitzpatrick, 2004; Healey, 2005; Spronken-Smith, 2005), traditional (and passive) lectures remain the dominant form of instruction in most undergraduate geoscience programs that are facing enrollment pressure. It is extremely difficult for undergraduate students to analyze, synthesize, and or integrate knowledge of complex processes and feedbacks that drive biophysical systems, based strictly on the material presented in the lectures and textbooks of geoscience courses. The majority of students have limited ability to remain engaged in the lecture (Penner, 1984), which was also observed by Davis (1887, 812):"*The attention of the class is not so well held by explanation from an instructor as by exploration for themselves*." Although field trips, study abroad programs, and internships provide an opportunity to provide students with a high impact experience that addresses several of these issues (Bishop, 2009; Houser et al., 2011; Houser et al., 2014; Lemmons et al., 2014), classes are increasingly restricted to the classroom, particularly large introductory service classes in which many students first discover the geosciences. In this respect, there is a need to supplement the traditional lecture through the use problem-based learning activities that reinforce the material learned in the classroom, and provides students with an opportunity to formalize and test their conceptual understanding of the material they learn in lecture and through readings.

Developing an inquiry approach to undergraduate education places an emphasis on active learning, development of conceptual understanding and reasoning skills (versus rote knowledge), and emphasis on students tackling the complexity, creativity, and discovery involved in science rather than assuming the existence of absolute knowledge (Halonen et al., 2003; Balaban, 2007). Specifically, inquiry-based is defined by the National Research Council (1996) as: "*a multifaceted activity that involves making observations; posing questions; examining books and other sources of information to see what is already known; planning investigations; reviewing what is already known in light of experimental evidence; using tools to gather, analyze, and interpret data; proposing answers, explanations, and predictions; and communicating the results. Inquiry requires identification of assumptions, use of critical and logical thinking, and consideration of alternative explanations*" (NRC, 1996, 23). In other words, inquiry-based activities allow the instructor to broaden the learning outcomes of a class with respect to knowledge,

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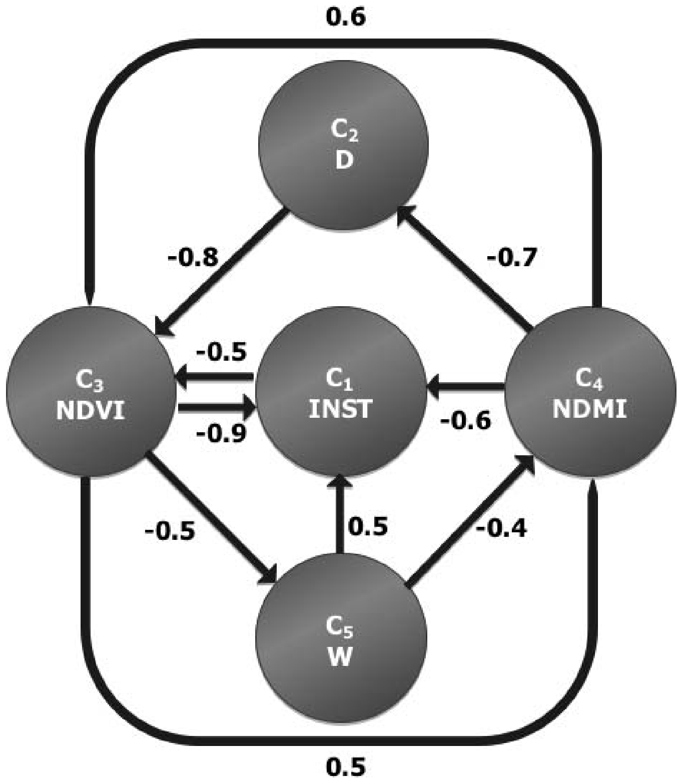


FIGURE 1: Analytical reasoning model for aeolian instability used to predict desertification (INST) by Houser et al. (2015). The nodes in Fig. 1 are assigned concept meanings (e.g., concept 1 [C1] is landscape instability [INST], C2 is drought scaled to the Palmer drought severity index (PDSI; D), C3 is vegetation cover (NDVI), C4 is surface moisture (NDMI), and C5 is wind (W).

skills, affective and learned abilities (Ewell, 2001), thereby giving the student ownership and responsibility for their learning. Inquiry-based learning leads not only to general and transferable inquiry skills, but also domain-specific skills (Edelson et al., 1999; Cerbin, 2000; Burgess and Taylor, 2000). More importantly, active learning makes it easier for the instructor to recognize misconceptions that the students have about the material discussed in class or presented in the textbook. However, it is important to note that with the right instructor traditional lectures can be exciting introductions to the geosciences that leaves students engaged and inspired, and that hands-on activities can also be viewed as tedious exercises and therefore not engaging. In other words, to suggest that traditional lectures are not as effective as practical exercises is oversimplistic and neglects the fact that traditional lectures tend to focus on the essential information on which the practical exercises are based.

Understanding processes and systems theory is perhaps best treated by mathematical formalization of process mechanics, forcing and feedback relationships, and nonlinear system dynamics. However, many concepts in the geosciences are not mathematically tractable or have not yet been formalized in the literature making it difficult for faculty or students to translate complex phenomena and feedbacks to the prototype landscape in undergraduate geoscience courses. It is particularly difficult where there is limited quantitative content in large classes or limited prerequisites in physics, math, and computer science (Bishop, 2009). Recent advances in geographic information science and technology (GIST) involving artificial intelligence (AI) and fuzzy systems permit the conceptual modeling of geoscience concepts that address STEM education issues involving knowledge representation, complex relationships, processes and feedbacks, coupled systems, and student engagement using geovisualization.

The purpose of this study is to develop and evaluate the use of analytical reasoning to teach complex concepts in the geosciences and promote thoughtful and meaningful student engagement. Students are asked to develop conceptual models based upon their understandings, and can compare and evaluate their knowledge based upon the visualization of conceptual models, and through analytical reasoning predictions that depict spatial patterns of concepts. The specific learning objectives of the assignment were to: (1) articulate the leading theories for desertification; (2) describe and simulate the complex feedbacks among atmospheric, ecological, and lithospheric variables in desertification; (3) demonstrate proficiency in using and interpreting geospatial data and information using appropriate software and processing strategies; and (4) exhibit the skills necessary to acquire, organize, reorganize, and interpret new knowledge through the development of conceptual models.

Analytical Reasoning

Conceptual models have long served as a means for geoscientists to organize their understanding of feedback mechanisms and complex systems and have served as a basis for human analytical reasoning and landscape interpretation (Houser et al., 2015). An example of conceptual modeling to understand the reactivation and stabilization of a dune field on the South Texas Sand Sheet near Corpus Christi, Texas, is presented in Fig. 1 (from Houser et al., 2015). The relatively simple conceptual model is like an earlier model developed by Muhs and Holliday (1995). Surface instability (a proxy for aeolian sediment transport) is inversely related to vegetation cover (Lancaster, 1988) and soil moisture and is directly dependent on the local wind speed. In turn, the wind speed is directly dependent on the relative elevation, whereas surface moisture is inversely dependent on elevation and wind speed and directly dependent on the vegetation cover. The nodes in Fig. 1 are assigned concept meanings (e.g., concept 1 [C1] is landscape instability [INST]; C2 is drought scaled to the Palmer drought severity index [PDSI; D]; C3 is vegetation cover [normalized difference vegetation index or NDVI]; C4 is surface moisture [normalized difference moisture index or NDMI] and C5 is wind [W]). Each of these concepts can be represented using biophysical information derived from geospatial data. For example, satellite multispectral data can be used to generate the NDVI that represents vegetation cover, and the NDMI depicts surface moisture variations. Land surface parameters generated from a digital elevation model (DEM) can be used as a proxy for wind speed. The arcs represent the relationships that are thought to exist between concepts, and the weight of an interaction defines the perceived direction and degree of causal influence amongst the concepts with a numerical value ranging from −1 (inverse) to +1 (direct). The concept nodes and weighted arcs are initially based on the conceptual knowledge of the user (i.e., the students), who

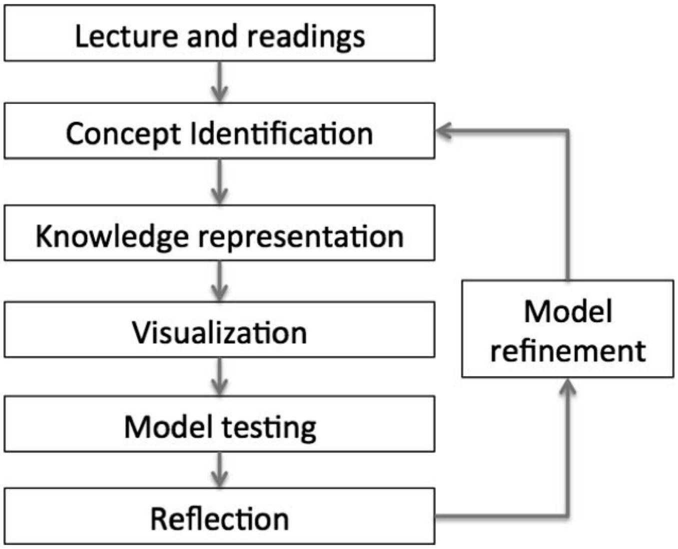


FIGURE 2. Observed distribution and extent of instability (i.e., open sands) for a drought of PDSI −0.52 (slight drought), which corresponds with a drought index of D = 0.5.

are asked to describe the strength and nature of each interconnection based on their understanding of the causality between concepts. As an educational tool, undergraduate students can be individually asked to formulate their understanding about a conceptual model (Papageorgiou et al., 2008), or the group of undergraduate students agrees to a set of linguistic rules as a group. Ultimately, the concepts, arcs, the strength of the relationships, and the scale at which landscape change can be modeled using this approach depend on the scale and complexity of the material covered in the lectures. Coarse-scale relationships that would be appropriate for an introductory geoscience class will require that the instructor use a small-scale (large area) remotely sensed image of low resolution. Decreasing the study size and increasing the resolution would allow for the consideration of relatively complex conceptual models in more advanced classes. In this respect, increases in model complexity need to be balanced against the size and resolution of the study area to ensure that computer time and resources do not affect the effectiveness of the technique.

Our example conceptual model encapsulates the basic knowledge about the stabilizing influence of vegetation and surface moisture, while accounting for the influence of topography on wind speed. In the "expert" model developed by the authors (see Houser et al., 2015), it was determined that vegetation has a moderate negative (inverse) relationship on wind speed, and given a causal value of −0.5. Thus, based upon our knowledge and field experience, we can produce a numerical weight matrix for the conceptual model illustrated in Fig. 1 as follows:

$$W=\{W_{ji}\}=\begin{bmatrix} 0 & 0 & -0.9 & -0.6 & 0.5 \\ 0 & 0 & 0 & -0.7 & 0 \\ -0.5 & -0.8 & 0 & 0.6 & 0 \\ 0 & 0 & 0.5 & 0 & -0.4 \\ 0 & 0 & -0.5 & 0 & 0 \end{bmatrix}, \qquad (1)$$

where the rows (i) and columns (j) systematically represent the concepts instability, drought, vegetation, surface moisture, and wind, respectively. For example, surface instability (top row) is inversely related to vegetation cover (third column) and this strong inverse relationship is given a causal value of −0.9 in the expert model. As an additional example, surface moisture (fourth row) is inversely related to wind speed (fifth column) and this relationship is given a causal relationship of −0.4 in the conceptual model and the weighted matrix (Eq. 1).

The initial value (A_i) of a concept (C_i) is either defined by an expert or represented by data from a remotely sensed imaged that is mapped onto the interval [0–1]. For example, vegetation cover is mapped from 0 (no vegetation) to 1 (maximum vegetation cover). Similarly, soil moisture is mapped from 0 (dry) to 1 (saturated). An iterative approach is used to update each value (A_i), by accounting for all possible influences derived from free interactions between map concepts:

$$A_i(k+1)=f\left(A_i(k)+\sum_{\substack{i=1,N\\ i\neq j}} A_j(k)W_{ji}\right), \qquad (2)$$

where, $A(k)=\{A_i, i=1,\ldots..N\}$ is a 1×N (row) vector that represents the value of C_i at iteration k, $W=\{W_{ji}, j,i=1,\ldots..N\}$ is the N×N matrix of causal connections (Eq. 1), and $f(\cdot)$ is a threshold function (we use a binary sigmoid function). In this respect, the resulting fuzzy cognitive map (FCM) is a dynamic system that: (1) converges to an equilibrium state, (2) converges to a limit cycle, or (3) exhibits a chaotic behavior in which the concepts change their values in a nondeterministic fashion (Furfaro et al., 2010). A FCM model is implemented at every grid cell over the landscape, driven by surface biophysical and topographic information, to produce spatial predictions of the primary concept. In this way, student knowledge is tested over the landscape based upon real-world geospatial data, such as the observed distribution of instability for a drought (D) of 0.5, which corresponds to a PDSI of −0.52. as presented in Fig. 2.

It is important to note that student engagement and use of this approach does not require the students or the faculty member has knowledge of computer programming or an understanding of the mathematics involved with analytical reasoning (Eqs. 1 and 2). To ensure that the model can be used by other faculty, training modules and documentation will need to be provided by the authors. It is, however, possible for the details and mathematics of the model to be slowly introduced into senior undergraduate and graduate courses as the concepts become increasingly complex and students develop stronger quantitative skills and confidence in GIS. A hierarchical approach would require further study of analytical reasoning in modeling landscape evolution and the ability of the model to be used and developed by faculty and students.

Analytical Reasoning GIS Activity: South Texas Sand Sheet

The use of analytical reasoning and FCMs to teach geoscience-related material, and introduce research into the undergraduate curriculum was tested in GEOG 331: Geomorphology (a junior/senior undergraduate class) in

TABLE I. Demographics of students participating in the analytical reasoning assignment.

	Number of Students
Sex	
Male	21
Female	14
Class	
Freshman (first year)	0
Sophomore (second year)	4
Junior (third year)	15
Senior (fourth year)	16
Major	
Geology	7
Environmental geoscience	4
Environmental studies	3
Geography	21

spring 2014 in the Department of Geography at Texas A&M University. Demographic data for the students participating in the analytical reasoning assignments are presented in Table I, and the steps completed by those students are presented in Fig. 3. After discussing aeolian processes and landforms at a coarse scale in the lecture and reading key papers on dune activation and stabilization (e.g., Werner, 1995; Kocurek and Lancaster, 1999; Hugenholtz and Wolfe, 2005a, 2005b; Hugenholtz et al., 2012; Barrineau et al., 2016), the undergraduate students were provided satellite imagery of the South Texas Sand Sheet including the: (1) DEM, (2) NDVI, and (3) NDMI. The students were then asked to discuss the relative importance of vegetation, wind speed, surface moisture, and regional drought (scaled to the PDSI) in controlling dune instability through the Holocene and in the future with a change in climate (concept identification; Fig. 3). Working in small learning communities (of four to five students), the students built the arcs and weightings based on their conceptual understanding of dune activation and stabilization and to predict the distribution of instability for a drought of $D = 0.5$ (see Fig. 2). The students arranged the concept nodes and establish causal relationships and magnitudes to represent their knowledge of how those concepts are interconnected. Specifically, students selected the causal connections and feedbacks between these concepts and select the magnitude of the strength of the relationships in a positive or negative direction to explicitly represent their knowledge of aeolian systems (knowledge representation; Fig. 1). Based on their collective understanding, each student group developed a different conceptual model that was then used to generate a predictive map of aeolian instability that was presented to the entire class during a subsequent lecture. Representative models developed by the students are presented in Fig. 4 showing both the predicted distribution of instability based on the corresponding interaction matrix. The development of the conceptual model by each group took about 15 min and was integrated into a regularly scheduled lecture period, although the development of the conceptual models can also be completed in a laboratory section and facilitated by a teaching assistant.

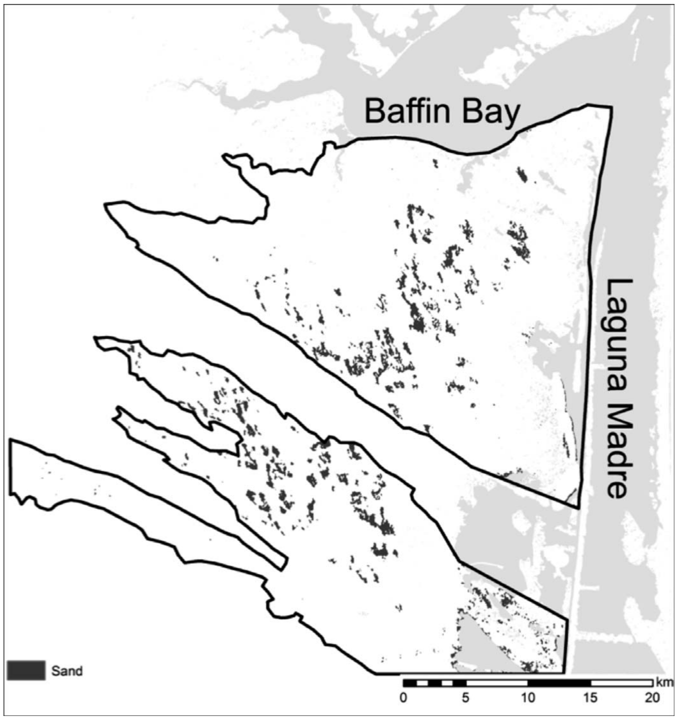
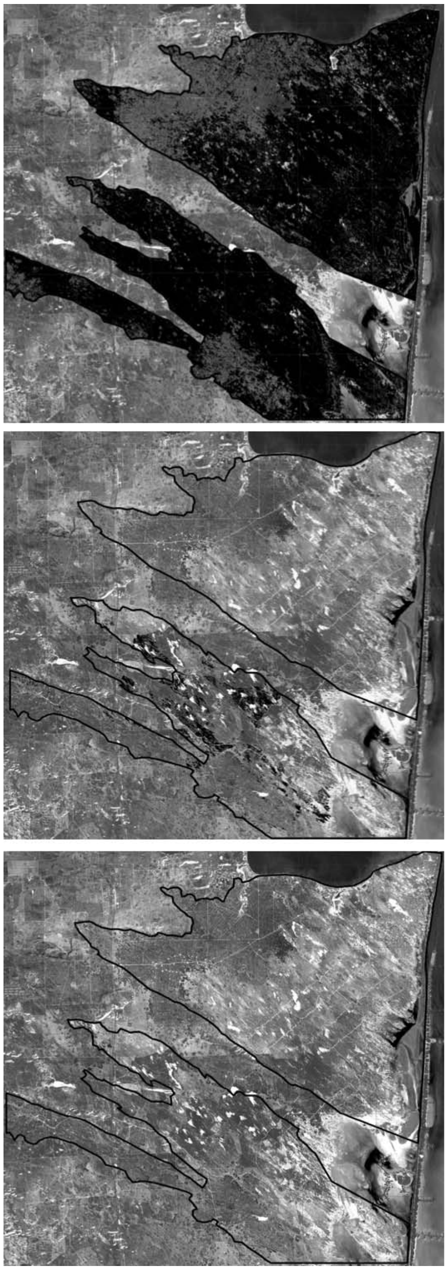


FIGURE 3. Steps completed by students as part of the analytical reasoning modeling.

The FCM algorithm (Eq. 2) was used to predict the spatial distribution of aeolian instability using a C++ program that runs on a Virtual Machine server (visualization; Fig. 3). The programming and analysis was completed by one of the authors (Bishop) and the results provided to the students in a subsequent class. The students are, therefore, not required to have knowledge of computer programming or an understanding of the mathematics involved with analytical reasoning using FCMs to complete this exercise. The students were given their model output and able to compare their model results with predicted instability from the "expert" model (model testing; Fig. 3), models developed by other learning communities in the class and the actual distribution of active sands (Fig. 2). This provided the students and the instructor (Houser) an opportunity to discuss misconceptions in their understanding of dune instability and how their conceptual model can be altered to increase the accuracy of their predictions. Specifically, students reflected on the reasoning behind their conceptual models and decided if the concepts, causal linkages and magnitudes needed to be changed (reflection; Fig. 3). Students were then asked to develop a new conceptual model that permits the exploration of other concepts that may be needed to accurately predict primary concept patterns. The opportunity to assess and explain their conceptual model and spatial predictions provides an opportunity to improve the traditional lecture through engagement and creativity, while demonstrating scientific principles of accuracy, repeatability, critical thinking, and systems theory.

Student Evaluation of Their Analytical Reasoning Models

There was considerable variability in the conceptual models developed by the groups (see Fig. 4), suggesting that



	INST	Drought	NDVI	NDMI	Wind
INST	0	0.1	-0.2	-0.5	0.2
Drought	0	0	-0.6	-0.9	0
NDVI	-0.2	-0.6	0	0.9	-0.5
NDMI	0	-0.9	0.9	0	-0.5
Wind	0	0	-0.5	-0.5	0

	INST	Drought	NDVI	NDMI	Wind
INST	0	0	-0.5	-0.5	0
Drought	0.9	0	-0.8	-1	0
NDVI	-0.5	-0.8	0	0.8	-0.7
NDMI	-0.5	-1	0.8	0	0
Wind	0.7	0	0	-0.2	0

	INST	Drought	NDVI	NDMI	Wind
INST	0	0	-0.7	-0.6	0
Drought	0.8	0	-0.9	-0.9	0
NDVI	-0.7	-0.9	0	0.9	-0.6
NDMI	-0.6	-0.9	0.9	0	0
Wind	0.8	0	-0.6	-0.2	0

FIGURE 4. Predicted distribution and extent of instability for a drought of D = 0.5 (PDSI = −0.52) developed by students. Shown are representative predicted instability maps and the corresponding interaction matrices for models that: (a) over-predict but are accurate, (b) under-predict and are inaccurate, and (c) do not predict instability. Predicted instability is shown as the black speckling across both regions of the study area in (a) and only in the southern part of the study area in (b).

the lectures and readings resulted in different and in some cases erroneous understanding of aeolian systems amongst the students. A comparison of the student models and the "expert" model is presented in Table II. The greatest variability was observed in the relationship between instability (i.e., active sand surface) and surface moisture, with some groups believing there to be a strong relationship between soil moisture and instability, whereas others believed that soil moisture had little to no influence on instability. Similarly, some groups believed that drought had a strong influence on vegetation, while others argued that the impact is not immediate (in time) and that the relationship is relatively weak. Although most groups believed that drought conditions had no direct influence on wind speed, one group believed that drought increased wind speed and another believed that it resulted in a decrease in wind speed. The conceptual model developed by the former group resulted in complete sand sheet activation due to the strong winds under drought conditions, whereas the latter group resulted in no active sand due to the weak winds. Comparison with the "expert" model, which can accurately predict the location and distribution of instability in the northern sand lobe (see Houser et al., 2015) allowed the students to determine why their conceptual understand-

TABLE II. Expert model used to predict instability as presented in Houser et al. (2015), standard deviation of weights in the models developed by the students and a comparison of the mean student weights used in their models compared with the weight used in the expert model. The largest differences among the students and the largest differences between the student model weights and the expert model weights are bold.

	INST	Drought	NDVI	NDMI	Wind
Expert model					
INST	0.0	0.0	−0.5	0.0	0.0
Drought	1.0	0.0	−0.8	0.0	0.0
NDVI	−0.9	0.0	0.0	0.5	−0.5
NDMI	−0.6	−0.7	0.6	0.0	0.0
Wind	0.5	0.0	0.0	−0.4	0.0
Standard deviation of student weights					
INST	0.0	0.0	0.2	0.2	0.1
Drought	**0.4**	0.0	0.1	0.1	0.0
NDVI	**0.2**	**0.3**	0.0	**0.3**	**0.4**
NDMI	**0.3**	**0.3**	0.1	0.0	0.2
Wind	**0.5**	**0.4**	**0.6**	0.2	0.0
Comparison of mean student weight to expert weight					
INST	0.0	0.0	0.1	**0.7**	0.0
Drought	**0.4**	0.0	−0.1	**1.0**	0.0
NDVI	**−0.3**	**0.6**	0.0	−0.2	−0.2
NDMI	0.0	0.1	−0.2	0.0	0.1
Wind	0.1	0.1	0.1	0.1	0.0

ing of aeolian systems were incorrect, and how they could modify the conceptual models to accurately predict the distribution and extent of active sands (model refinement; Fig. 3). The ability for students to revisit and improve their models after instructor feedback is one of the most important aspects of using analytical reasoning because students can take ownership of their learning by recognizing where their work can be improved.

Student Evaluation of Analytical Reasoning

After the students were presented with the results of their conceptual models and had an opportunity to refine their models, all students were invited to participate in a debriefing focus group immediately following the class in which they assessed and revised their models relative to observed changes in surface instability with drought conditions and the expert model. The focus group lasted about 15–20 min, and 89% of the class (31/35) participated, and only those students who participated in the analytical reasoning models (35/35) were permitted to participate in the focus groups. The focus group was administered by the third author, who was not involved in the class, but is experienced in physical geography and geoscience education to maintain anonymity of the students, and to encourage more explicit answers. During the focus group students were asked to complete a survey and provide a verbal description about the use of traditional lectures supplemented by analytical reasoning assignments versus traditional lectures alone.

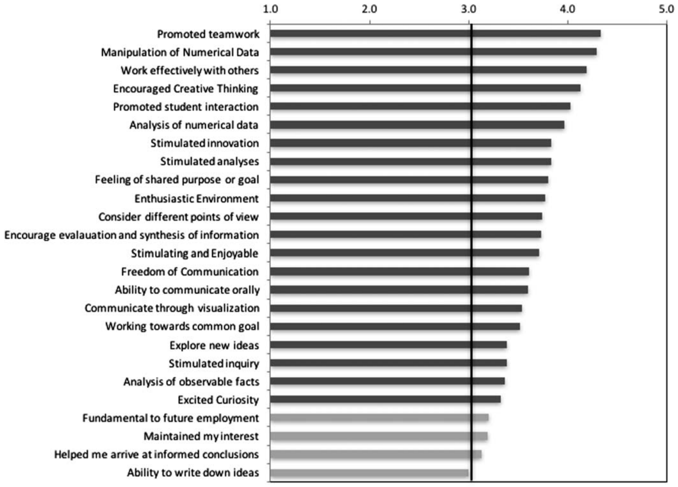


FIGURE 5. Mean response of students who completed an analytical reasoning module in a geomorphology class. Students describe the experience on a Likert scale from 1 (traditional lecture without analytical reasoning supplement is better) to 5 (lecture with analytical reasoning supplement is better). The analytical reasoning approach was perceived by the students as significantly better (at the 95% confidence level) for the learning outcomes with the red (darker) bars based on a *t*-test analysis.

Survey Results

In the survey, the students were asked to evaluate various aspects of the experience on a Likert scale from 1 (traditional lecture is better) to 5 (analytical reasoning approach is better) in a paper survey. Following Norman (2010) and de Winter and Dodou (2010), we used the parametric *t*-test to determine if the mean student response was significantly different from 3 (no difference between traditional lectures supplemented by analytical reasoning assignments versus traditional lectures alone). As shown in Fig. 5, the students ($n = 31$) described the analytical reasoning approach as being significantly better (at the 95% confidence level) for understanding the expansion and contraction of deserts, with the greatest benefits perceived in the areas of working with data, teamwork, student interaction, innovation, and creative thinking. Another reason for administering the focus group in this research was to provide complementary and contextual data. Lemmons (2015, 547) notes that "*complementing adds the descriptive element*" that is needed to gain greater insight into research findings. No statistically significant difference was observed in the responses among sex, major, and class (freshman, sophomore, junior, or senior), but further testing with multiple cohorts and a control group is required to explore the potential for this approach to teaching complex concepts in the geosciences and the ability to propagate this technique across other geoscience courses and programs.

Student Responses

When the students completed the survey, they were asked to describe their experience with analytical reasoning using the questions provided in Table III as prompts. Responses were recorded, transcribed, and coded by the third author, following procedures discussed by Cope (2003).

TABLE III. Questions used to prompt student responses about their experience with the analytical reasoning assignment based on a rubric by Kaufman and Mann (1996).

Learning environment	What do you think about this analytical reasoning approach? How does it compare with a traditional lecture and lab approach?
	Have you had experience with problem-based learning in the past?
	Do you want to see more problem-based learning in the future?
	Which method promoted interaction?
	Which method maintained your interest?
	How could this analytical reasoning approach be improved?
	Which method was stimulating and enjoyable?
Curriculum	Which method excited your curiosity about the science?

The student descriptions of analytical reasoning are "complementary" data to the Likert scale findings and representative responses are provided in this section. Comparing traditional lectures supplemented by analytical reasoning assignments with traditional lectures, one student noted, "*I think you can cover more material with a traditional style [lecture], but you can dig deeper and learn more with these [FCMs]*." Another student noted that they "*prefer problem based learning, [because] I nod off during lecture,*" while another commented that the approach helps "*to reinforce the material…to learn it for yourself*." This assessment of the technique suggests that analytical reasoning is an effective means for the students to both master the domain knowledge, but also to build transferable skills in problem solving. Another student commented that it would not be possible to "*use this approach without a normal lecture to provide the background material,*" suggesting that analytical reasoning supports, and is best used in combination with, the traditional lecture, and therefore represents a new way for instructors to "*flip a class*."

Implementing in the Earth Science Curriculum

An analytical reasoning approach can be used to introduce and explore complex geosystems across an earth science curriculum. For example, analytical reasoning can be used in geoscience classes in which students are required to explore fundamental geographic and earth-science concepts including but not limited to forest fire potential, climate-cryosphere feedbacks, landslide prediction, mountain building, and coastal erosion. Introduction of these concepts into geoscience classes will allow for more complex and coupled human-natural systems to be explored in upper-division and graduate classes. Regardless of the focus, each analytical reasoning module that is developed requires the following components:

1. **Concept Identification**: Each learning community will identify the key concepts that they perceive as being important for predicting. The selection of these concepts will be based on their understanding of the topic from the introductory lecture and associated readings.
2. **Knowledge Representation**: The students arrange concept nodes and establish causal relationships and magnitudes to represent their knowledge of how those concepts are interconnected. The semantic definitions developed by the students will determine the nature of geospatial data that will be used as a proxy for representing the concept, or whether the concept should be a spatially static value.
3. **Geovisualization:** The computer program will then generate a predictive map (fire potential, desertification, etc.) based on the conceptual model developed by the student.
4. **Model testing:** Students will then be able to compare their model results to known patterns from that landscape. Students will also be able to compare their spatial predictions against an expert conceptual model (developed by the participating faculty).
5. **Reflection and model refinement:** In learning groups, students will then discuss the reasoning behind their conceptual models and decide if the concepts, causal linkages, and magnitudes need to be changed. Students will be asked to develop a new conceptual model that permits the exploration of other concepts that may be needed to accurately predict primary concept patterns.

Through this approach, the instructor can broaden the learning outcomes of the course with respect to knowledge, skills, and affective and learned abilities (Ewell, 2001), thereby giving the student ownership and responsibility for their learning.

Study Limitations

It is important to note that this analysis is limited to student perceptions of their own learning, and there is a need to conduct further tests using independent measures of student learning gains (e.g., no pre/posttest or comparison between the intervention group and a control group) to accurately assess the use of analytical reasoning in the classroom. This testing will ensure that analytical reasoning has the potential to transform undergraduate education in the geosciences by providing students an opportunity to formalize and test their conceptual understanding of the material they learn in lecture and through readings, consistent with the definition of inquiry-based learning provide by the National Research Council (1996). Although there will always be a need for the formal lecture to present the fundamental concepts to the students, analytical reasoning provides a means to effectively decrease the lecture while increasing learning.

Summary

The primary goal of this study was to provide undergraduate students with a rigorous and integrative education and research experience. Integration of analytical reasoning and learning communities with traditional lectures allows instructors to develop broader learning outcomes including collaboration, communication, critical thinking, and personal and social responsibility. The ability to compare the results of their conceptual models to real-world features allows the students to recognize their own misconceptions about the material covered in the lectures and reading materials. The analytical reasoning approach provides undergraduate students enrolled in a geoscience class with "*opportunities to learn through inquiry rather than simple transmission of knowledge, as the first in a bill of rights for undergraduate education*" (Boyer, 1998). Moreover, an analytical reasoning approach to geoscience concepts strengthens the students' quantitative skills and exposes them to geospatial data and technologies that are collectively used to study and map the physical landscape (e.g., Bailey et al., 2000; Kim and Bednarz, 2013). Most geoscience courses and programs have not kept pace with the rapidly evolving field of GIST, and consequently, there has been little integration of state-of-the-art GIST in the classroom (Hoffman and Barstow, 2007; Bishop, 2009; Harrower et al., 2013).

Implementing a knowledge representation and scientific inquiry approach to undergraduate education through analytical reasoning modules places an emphasis on creativity, active and engaged learning, conceptual understanding and reasoning, exploration of relationships and complexity, and information and knowledge discovery, rather than knowing a collection of facts (Halonen et al., 2003; Balaban, 2007). In other words, scientific inquiry-based learning allows the instructor to broaden the learning outcomes with respect to discipline knowledge, skill sets, and learned abilities (Ewell, 2001), thereby giving the students ownership and responsibility for their learning. Inquiry-based learning leads not only to general and transferable inquiry skills, but also domain-specific skills (Edelson et al., 1999; Burgess and Taylor, 2000; Cerbin, 2000). The approach described in this paper enables students to "*encode*" their knowledge and compare modeling results to real-world spatial features and patterns, which will make it easier for the instructor to recognize misconceptions that the students have about the material presented in class and in the textbook. More importantly, the students will be able to recognize their own misconceptions about the material covered in the course, and modules will promote reflective learning. The preliminary results of this study suggest that students perceived that the analytical reasoning approach was significantly better for understanding the expansion and contraction of deserts compared with the traditional lecture, with the greatest benefits perceived in the areas of working with data, teamwork, student interaction, innovation, and creative thinking. However, it is important to note that the analytical reasoning exercise would not have been a positive experience without effective and engaging transfer of essential concepts through a series of lectures. In this respect, analytical reasoning provides an effective way of enhancing and increasing student engagement with the material introduced in lectures that can also be inspiring with the right instructor. The opportunity to incorporate anthropogenic forces in the analytical reasoning model will allow future students to examine complex human-environment issues as desertification, but further testing with multiple cohorts and a control group is required to determine the full potential of analytical reasoning in geoscience classes.

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