Sustainable Development: It's as easy as F-E-W[1]

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Summary: This lesson presents a framework for exploring challenges associated with sustainable management of food, energy, and water (FEW) resources in user-defined case study locations using a combination of jigsaw and role playing methods. In the base scenario described in this lesson plan students are presented with U.S. regions that have an uneven distribution of resources; for example, the Pacific Northwest has ample water while other regions are water-limited but are rich in fertile land (e.g., the Midwest) or in sunlight for electricity production (e.g., Mojave desert). In this lesson, students use concept maps to evaluate the various natural and social factors influencing a community's ability to secure and utilize these critical resources. Then, working in groups, students propose a sustainable development policy specific to their community's needs and evaluate its effectiveness using a game-based approach. This lesson (and associated case study framework) is designed for use in introductory courses of any discipline that address management of natural resources by communities in some capacity; suggestions are provided throughout the handout on ways to modify the content to reflect a specific course focus or course level. This lesson can be implemented in three 50-minute class periods.

Learning Goals & Objectives: This case-based lesson generally aims to improve students' understanding of interactions between natural and social systems as well as increase their abilities to communicate and build consensus. Specifically, as a result of this FEW lesson, the students should be able to:

- Describe the key characteristics of FEW systems
- Compare and contrast management approaches for FEW systems (including interconnections)
- Evaluate community resilience and sustainability in the context of FEW systems

Depending on the course in which it is embedded, the lesson can also be used as a "hook" to develop socio-cultural awareness of different regions and develop students' abilities to do integrative research by incorporating data analytics and modeling.

Topical areas: Environmental science, natural resources management, community resilience, environmental sociology, environmental engineering, social enterprise/innovation, environmental policy, agent-based or systems dynamic modeling, and urban and regional planning.

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[1] We are interested in improving this lesson and general case study framework as well as in tracking their use. Please contact Dr. Thushara Gunda at tgunda [at] sandia [dot] gov with comments on the use of this plan and any suggestions for improvement.

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Introduction

You and your fellow countrymen and women have arrived in a new land that is rich in fertile soil, water, and minerals. However, within this land there is no single area that is well endowed with all three of these important resources.

- *Scouts report that the Northwest region is a beautiful landscape of snowcapped peaks and lush green hills woven together by an intricate network of gleaming strands of silvery water. However, they have not detected any significant sources of fertile land or minerals.*
- *Scouts describe the Central region of the land as a sea of endless plains and rolling grasslands covered in rich loamy soil and cut across by large rivers. They note, however, that most of the land is untouched by natural waterways and that few mineral sources were discovered.*
- *Finally, the scouts investigating the Southwest region report that, in the rough wilderness and mountains of sand, they found numerous sites where gleaming minerals could be harvested to generate energy. However, they note that the rocky terrain is not amenable to farming nor is there much water in the region.*

Your fellow settlers could not come to an agreement about where to establish your home base. So by unanimous decision, you decide to split up into 3 communities, one in each of the 3 regions. Your goal is to settle this land and develop a prosperous and long-lived society at your community's location.

*Variation for collaborative development: "*By unanimous decision you have decided to spread out and develop communities in different regions of this new land. Your goal is to work together to settle this land and develop a prosperous and long-lived society for all of the settlers, across the three community locations."[2]

However, upon arriving at your assigned destination, you have come to the realization that you don't know the first thing about managing the natural resources in your area in order to sustainably develop your community. The success of your community depends on your ability to develop sound strategies for natural resource development and utilization. Therefore, you task your three most trusted advisors with studying the intricacies of three products that you feel are critical to maintaining and developing your community: drinking water, food, and electricity. Armed with this knowledge, you plan to craft robust policies that will allow your community to prosper and thrive through good times and bad for countless generations.

However, you wonder if this will be enough. Only time will tell, as this sustainable development adventure starts now!

[2] Text in gray highlights possible variations that can be made to the lesson in *both* the teacher and student handouts.

Natural resources are rarely distributed uniformly. Often a region may have bountiful resources of water, but not necessarily fertile soil or conditions suitable for sustainable electricity production. Historically, communities with ample water sources used it for multiple purposes, including hydropower generation, while areas with limited water resources depended on groundwater to help meet their needs. However, climate change is challenging communities' abilities to access critical resources, with increasing temperatures and increasing variability in precipitation affecting local water supplies and crop production. Furthermore, population growth and changing lifestyles increase resource demands, leading to issues such as over-drafting of groundwater and increasing impact to aquatic habitats, which can influence the long-term resilience of a community. Increasingly then, communities need to formulate robust strategies that allow them to not only develop sustainably, but to also address resource scarcity issues in a resilient manner. This lesson challenges the students to not only understand an individual resource-derived product (such as food), but to also explore the complex connections between resource management and overall community (or system) behavior.

The development of any effective strategy first requires an understanding of the various factors driving the processes of interest as well as their interactions within a system so that unintended consequences can be minimized. This lesson begins with students developing individual product concept maps and integrated food-energy-water (FEW) concept maps prior to developing community policies and implementing them in a game setting. Note: although this lesson is designed for use in introductory courses that address natural resources, communities, and/or planning, we assume that students have a basic understanding of food, energy, and water resources; systems thinking; and concept maps prior to the implementation of this lesson; resources are provided throughout this document (especially in the Appendices) that can be used as refreshers on key concepts.

This lesson presents a general framework regarding FEW resources that can be used to develop a case study using specific details about a given place. Various aspects of this case study framework can be modified to reflect the specific class/context in which it is implemented. For example, the framework uses generalized characteristics modeled after U.S. regions to establish context (e.g., Pacific Northwest as the water-rich region, Midwest as the fertile land-rich region, and the Mojave Desert in the Southwest as the mineral-rich region). However, the regional bases can be easily modified to reflect the specific class or context in which the lesson is implemented (for e.g., Brazil can serve as the basis for the water-rich region, India for the fertile-land, and Saudi Arabia for the mineral-rich region). The context could also be refined to reflect three special interest groups within the same city or other political jurisdiction. Throughout this handout, we present possible variations of the original materials, including aspects related to framing the problem (e.g., the variation of collaborative development in the hook) and to different disciplines/course levels. Some of the text in the teacher's handout overlaps with text in the student's handout (notably the framing, game directions, and rubrics). We use gray text in this document to highlight those variations that can also directly impact the content currently presented in the student handout.

Note: this lesson does make a distinction between FEW resources that naturally occur and products that are available for direct consumption; the latter require some form of investment (either transportation or conversion) before they can be used by humans directly. For example, freshwater is a resource while drinking water is a product, because the latter undergoes treatment and conveyance prior to being available for human consumption. Similarly, food is a product that requires an investment of resources such as water and fertile land as well as other products such as diesel to operate groundwater pumps. Last but not least, electricity is a product, which can be developed using various forms of energy sources, including solar, wind, and fossil fuels.

Learning Goals & Objectives

The specific learning goals addressed by this lesson are: 1) an understanding of interactions between natural and social systems and thus, systems thinking and 2) communication of complex issues with peers from different backgrounds and experiences. Throughout the course of these lessons, the students will be challenged to communicate and build consensus within their product and community groups. Depending on the class focus, socio-cultural awareness can be more actively incorporated into the case study.

As a result of this FEW lesson, the students should be able to:

- Describe the key characteristics of FEW systems
- Compare and contrast management approaches for FEW systems (including interconnections)
- Evaluate community resilience and sustainability in the context of FEW systems

For more advanced courses, data and modeling components could be more actively integrated into the lesson's learning objectives and design.

Classes Overview

The FEW lesson can be successfully implemented in three 50-minute class periods; for longer class periods, the suggested times for each activity could be extended. Table 1 summarizes the layout of the case activities, estimated times, and their alignment with the learning goals and objectives; if the students have little domain knowledge about FEW domains or systems mapping, we encourage extending the suggested activity times into additional periods as needed. The subsequent sections describe specific logistics and assessments associated with each class period. The general organization of student groups in each class periods follows a jigsaw method, which is summarized in Figure 1. In the first class, the students work within their individual product groups to understand the factors governing their assigned product. Then, in the second class, they are reorganized into community-based groups to explore interconnections between the three FEW products and develop their community policy strategy. Then, in the third class, the students return to their original product-based groups (but now representing their community policy preferences) to play the game. We encourage the instructors to review the content and modify the suggested activities and assessments as necessary to align with their course teaching goals.

Table 1. Summary of Classes

Class	Learning Objective	Pre-class activity	During Class	After class (i.e., homework)	Assessment
1	Describe the key characteristics of FEW systems	Develop concept map for assigned product (Individual Deliverable)	1. In product-specific groups, have students come to a consensus on concept map (~25 min) 2. Present lecture on foundations of resilience (or other class focus) (~10 min) 3. Have students incorporate resilience into their product concept map (Group Deliverable) (~15 min)	None	Formative: See Rubric #1 for evaluation of product concept maps
2	Compare and contrast management approaches for FEW systems (including interconnections)	None	1. In community groups, create a single concept map integrating FEW concepts (~25 min) 2. Group presentation to class on integrated FEW map (Group Deliverable) (~15 min) 3. Formulate a strategy/policy for community development (~10 min) (may need to finish outside of class in groups)	Pro-con grid (Individual Deliverable) Read game rules	Formative: See Rubric #2 for evaluation of integrated FEW concept map and oral presentations Formative: See Rubric #3 for evaluation of pro-con grid
3	Measure, estimate, and evaluate community resilience and sustainability in the context of FEW systems	(see homework from Class 2)	1. Explain game rules (~15 min) 2. Divide students into groups to play game (~25 min) 3. Facilitate post-game discussion (~10 min)	Policy brief (Individual or Group Deliverable)	Summative: See Rubric #4 for evaluation of policy brief

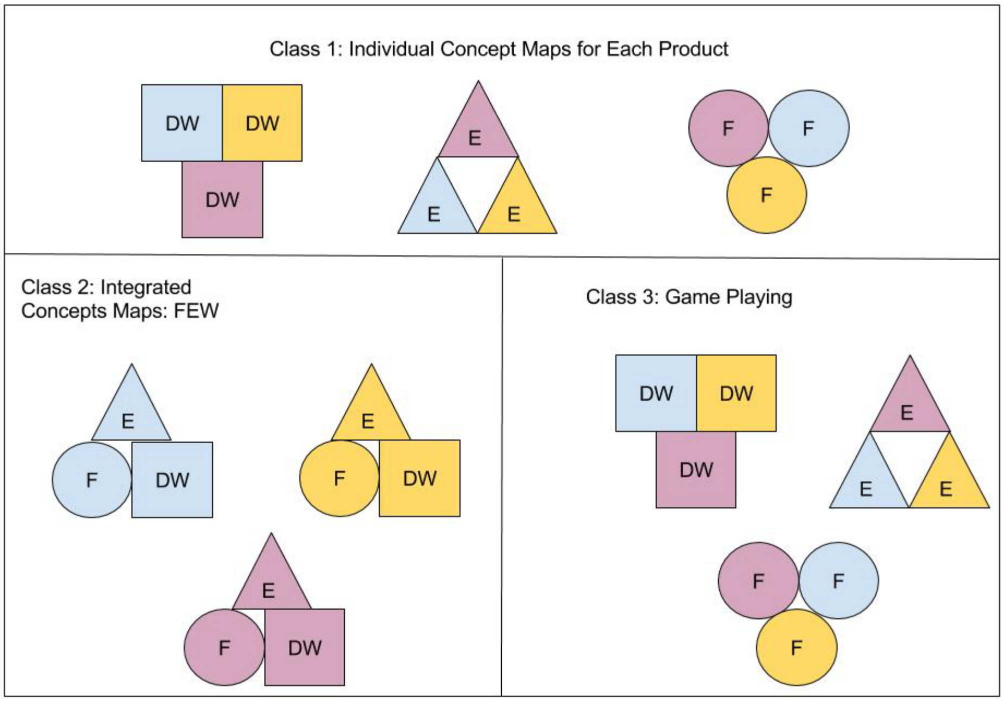

Figure 1. Organization of student groups during the three classes. The letters refer to product assigned for initial concept map development (DW = drinking water; E = electricity; F = food). The colors refer to the community assignments (blue = Northwest; yellow = Central; purple = Southwest).

1. Prior to Class 1

Prior to class 1, the students should be assigned to one of the three product groups (food, electricity, or drinking water), for which they develop a concept map. A concept map is a type of flowchart that connects key concepts (aka nodes) with each other using directional arrows that elucidate the interactions.[3] Concept maps have been successfully implemented as a teaching technique for promoting complex systems thinking[4] by explicitly depicting the (often implicit) connections between variables.[5] Concept maps can either be hand-drawn or developed using https://cmap.ihmc.us/ or http://www.mentalmodeler.com/; there are resources describing the use of the online tools on their respective webpages. The full description for the concept map assignment to be completed for class 1 can be found in the Student Handout; for this lesson, we assume the students already know the basics of concept maps.[6] We strongly recommend laying out the general lesson plan (including the scope of the

[3] A good overview of concept maps, their structure, and their advantage from an assessment standpoint are discussed here: http://ar.cetl.hku.hk/am_cm.htm

[4] Deaton, M.L., Wei, C.A., and Weng Y-C. Concept Mapping: A technique for teaching about systems and complex problems.

[5] Stewart, M. (2012) Joined up thinking: Evaluating the use of concept mapping to develop complex systems learning. *Assessment & Evaluation in Higher Education,* 37:3, 349-368, DOI: 10.1080/02602938.2010.534764.

[6] A good overview of concept maps can also be found in the Appendix of the following case study: https://www.sesync.org/system/tdf/resources/tutorial_1_overview_of_socio-environmental_synthesis_0.pdf?file=1&type=node&id=967&force=

game) for the students so that they have a sense of the end goal prior to class 1.

If the students do not have a basic foundation in food, energy, and water systems, then consider devoting an additional class period to reviewing the content/references presented in Appendices, which includes background information on the three resources. Readings could also be assigned to reflect the framing of the course (e.g., environmental justice).

2. Class 1: Product-oriented concept maps and resilience

During the first class, the students should congregate in their product-oriented groups (Figure 1), in which they will share their individual maps and work towards a group consensus. After the students come to a consensus for their group's concept map for their assigned product (~25 min), they should be challenged to review their group's map in the context of resiliency (~15 min). The Appendices section on resilience contains a review of important principles and references should students need a refresher (~10 min).

Depending on the focus of the course, the framing could be revised from resilience to another concept (e.g., sustainability, equity, or growth), could be used to probe local cultural norms and histories, or could be used to probe limiting factors for the production process in a technical/engineering-oriented class. Some background information on sustainability is provided in the appendices; lecture material integrating this concept with one of the resources (energy) is provided in the supplementary material file.

We recommend assigning the individual concept map as a completion grade and reviewing the group concept map deliverable using Rubric 1. Each product's concept map should address the following three elements to some degree:

- Source, treatment/processing, distribution, and waste phases of the product
- Connections (if any) to other two products (if any) that could occur
- Interactions with natural resources

An example concept map for drinking water is presented in Figure 2. A written assignment could also be added to have the students reflect on which aspects of their individually-drawn concept maps for a given product were not included in the overall group concept map for that product.

Class 1 Breakdown:

- Build group consensus on concept map for assigned product – 25 minutes
- Present background material on resilience (or alternative framing concept) – 10 minutes (if needed)
- Group revision of product concept map in the context of resilience – 15 minutes
- Collect individual product concept maps (pre-class assignment)
- Collect group final product concept maps (in-class assignment)

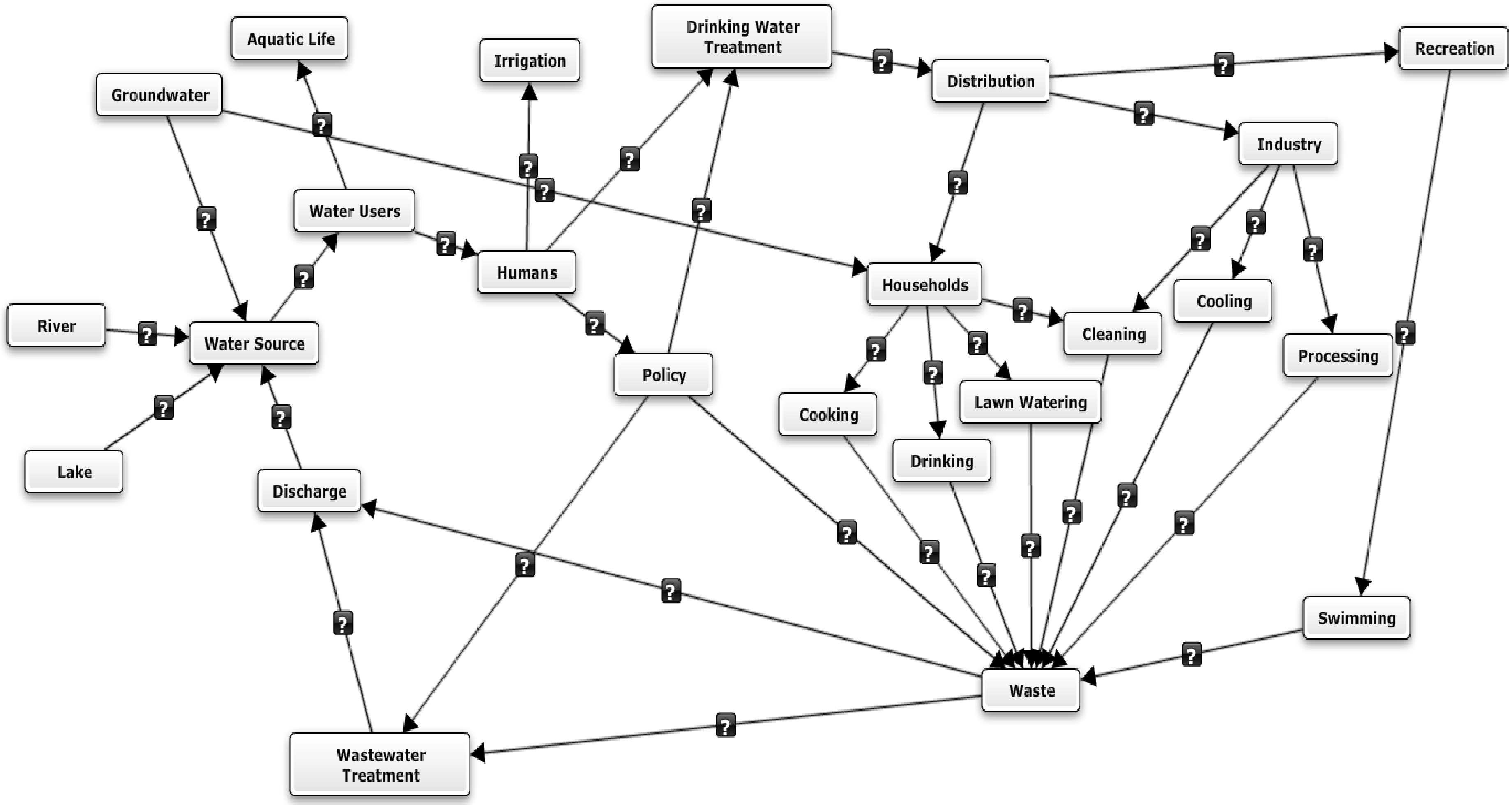

Figure 2. Example concept map for drinking water (without resilience framework included). The concept map covers different phases (e.g., source and treatment) and interactions between nature and people. Connections to food and electricity are implied as part of the irrigation and treatment concepts. The ?'s represent unknown magnitude and direction (input = 0) of impacts that could be populated in Mental Modeler.

Rubric #1: Product Concept Map

Grading Criteria	**Excellent - A** (5 points)	**Adequate - C** (3 points)	**Fail - F** (1 point)	**Points awarded**
Natural and Social Concepts	Addresses multiple natural and social factors influencing various phases of human-product interactions	Addresses some natural and social factors influencing some phases of human-product interactions	Overlooks most natural and social factors of human-product interactions	
Resilience	Map demonstrates many factor interactions that could enable or hinder community resilience	Map demonstrates few factor interactions that could enable or hinder community resilience	Resilience considerations in map are not obvious	
Structure	Non-linear structure of map indicates complex thinking about the meaningful relationships between natural factors, social factors, and resilience	Map shows definite thinking about relationships between natural factors, social factors, and resilience	Thinking process is not clear and presents to be cluttered; inappropriate structure	
Communication	Information is presented clearly and allows for a high level of understanding	Information is presented clearly and allows for a basic level of understanding	Information is not clear, very difficult to understand	
			Total Points (out of 20)	

Detailed Feedback/Critique:

3. Class 2: Community-oriented FEW concept maps

The focus of this class period is to have the students compare and contrast management approaches for FEW systems (including interconnections). At the beginning of the class, the students should be assigned to one of three communities (e.g., Northwest, Midwest, or Southwest) such that a student from each product (i.e., food, drinking water, and electricity) is represented in each community. Ideally, the groups would be limited to three students each. Within their community groups, the students are tasked with generating a single concept map that integrates all three products (~25 min). Upon completion of the activity, each group presents their map to the class (~15 min). The community-based FEW concept maps and associated oral presentations can be assessed formatively (See Rubric 2). Approximately 15 minutes is allocated for group presentations so if there are more than 5 groups in the class (i.e., 3 minutes per group), then consider having 2 groups present to each other instead (note: based on experience, the full class discussion may be more enriching than the smaller groupings). With any remaining class time (~10 min), the students are tasked with formulating a strategy/policy that will guide their community's development strategy during gameplay in Class 3. Encourage the students to spend time developing and recording a clear strategy (that includes how they will interact with their neighbors) since they will need to reflect on the effectiveness of their strategy as part of their policy brief at the end of Class 3. Since the students are developing policies specific to a particular community, consider sharing the game board layout with them ahead of time to inform their efforts.

After class, the students are tasked with: 1) finishing their community development strategy, 2) completing a pro-con grid and 3) reading the game rules. The pro-con grid asks the students to reflect on their original product assignment and challenges associated with developing an integrated FEW concept map and community development strategy. In other words, what aspects of their own product concept map did not make it into the FEW concept map and why? What were the benefits and drawbacks associated with the community-level planning? What are potential issues with basing community plans on individual product concept maps? How do the identified benefits and drawbacks vary in their level of impact to the community? The detailed description for the pro-con grid assignment can be found in the Student Handout. Note: the pro-con grid is not meant to be an extensive exercise (suggested length is approximately half a page); it is intended to set the stage for the reflection/writing aspects associated with the lesson's final assignment. The formative assessment associated with the pro-con grid can be assessed using Rubric 3. Depending on the class focus, stakeholder inclusion could be incorporated, potentially with a rainbow analysis. [7] The rainbow analysis could complement the pro-con grid as a way to consider who benefits from which decisions and at whose expense. Note: the students do not turn in their community strategy prior to Class 3 (although this can be modified).

Class 2 Breakdown:

- In community groups, create an integrated FEW concept map – 25 minutes
- Group presentation of integrated FEW concept maps to class – 15 minutes
- In community groups, formulate a sustainable development strategy – 10 minutes
- Assign completion of community strategy, pro-con grid, and reading of game rules

[7] Chevalier, J.M., Buckles, D.J., 2008. SAS2: a Guide to Collaborative Inquiry and Social Engagement. Sage Publications.

Rubric #2: Integrated FEW Concept Map[8]

	5	**3**	**1**	**Points Awarded**
FEW Integrated CM: Does your concept map (CM) address social and natural factors for all three products? Does it consider their interactions in multiple ways? Does it consider challenges faced by your particular community?	CM addresses interactions across all three resources (i.e., covers all of the green zone) and includes challenges a specific community might face	Some interactions between resources are considered and it is unclear how a community's challenges might interact with CM	Resource interactions are very limited (i.e., mostly in the black zone). No community challenges are apparent in the CM.	
Group/Team: Does your team include the diversity of expertise necessary to accomplish your goals? Has your team engaged a strong team of advisors and/or engaged with peer reviewed literature?	Team demonstrates a solid base of expertise and has clearly consulted an array of resources.	Team demonstrates some experience and some resources.	Team has not connected with potential resources and it does not display much experience.	
Presentation and Other Strengths: Was your presentation professional and well-practiced? Is there anything else that your team has done exceptionally well?	Team demonstrates exceptional, participatory presentation skills that integrate all team members' strengths and abilities. Team is professional in appearance, and is strong in its overall cohesion and related skills	Team demonstrates moderate presentation and team cohesion/related skills, but would benefit from further guidance and practice	Team is not comfortable or is ineffective in presentation skills and/or team cohesion and related skills	
Demonstration of progress through the challenge: What has your team learned in the process of working on integrated FEW CM?	Team demonstrates significant learning around FEW nexus, collaboration and the competencies to bring them all together.	Team demonstrates some learning but still has significant gaps that could be barriers to understanding FEW nexus.	Team has not demonstrated significant learning about FEW nexus	
			Total Score (out of 20)	

Detailed Feedback/Critique:

[8] The green and black colors in the rubric refer to the grading cheat sheet provided in the student handout

Rubric #3: Pro-Con Grid

Criteria	**5**	**3**	**1**	**Points Awarded**
Pros: Does the assignment capture benefits of a product-specific concept map? Does it address more than one product? Does it identify benefits of an integrated FEW concept map?	Has articulated more than two benefits of a product-specific concept map, addressing more than one product's perspective, and identified at least one benefit of an integrated concept map	Has articulated two benefits of a product-specific concept map, does not address more than one product's perspective or the benefits of an integrated concept map	No benefits of a product-specific or integrated concept map were articulated	
Cons: Does the assignment capture challenges associated with developing an integrated FEW concept map? Does it identify potential pitfalls in product-oriented planning?	Has articulated more than two challenges of FEW concept map, and at least one potential issues with product-oriented planning	Has articulated two challenges of FEW concept map, does not identify potential issues around product-oriented planning	No challenges of FEW concept map development or issues with product-oriented planning were articulated	
Resilience: Are the associated social impacts of the pro-cons discussed? How is community resilience enhanced or hindered by the pro-cons?	Displays a solid potential to make the community sustainable. Has clearly defined the potential for exceptional impact.	Has thought about how to make the community sustainable, but still has significant gaps in its viability.	Does not have a viable plan for how to sustain the community.	
Communication: Is the writing easy to follow and understand? Does the style and organization enhance reader comprehension?	Writing style is clear and well-organized, thus facilitating reader comprehension	Main points are there but writing style is only somewhat clear and organized	Unclear what the sentences mean or how they relate to each other	
			Total points (out of 20)	

Detailed feedback/critique:

4. Class 3: Game play

The focus of class 3 is to play a board game in which the students implement their community development strategy. Game-based learning is becoming increasingly popular in teaching settings;[9] a significant advantage of a game-based approach is that they allow the students to experience real-world issues and challenges that are not otherwise possible. "Serious" games are designed using standard game design principles and methodologies but are designed for purposes other than entertainment.[10] Incorporating games presents an opportunity for undergraduate students to both learn and get interested in contemporary topics such as FEW nexus. Furthermore, gamification allows the incorporation of soft-skills building, such as critical thinking, negotiating, creative problem solving, and teamwork (Kapp, 2012; Johnson et al., 2012).[11] Multi-player games, in contrast to single-player games, have been shown to engage students and further increase their interactions with peers and improve their individual communication strategies (Medema et al., 2016).[12] We have designed a multiplayer game that allows students to use soft-skills and engage in social learning through collaboration and negotiation. Note that incorporation of immediate feedback (either during game play or as part of the game debrief) is critical to the success of a game-based learning effort.

The FEW game is generally designed after Settlers of Catan™ and requires students to use resources to develop products and establish their communities (Figure 3). The game activity is summarized in the overview and game rules sections below (in these sections, note that the text in black reflects information presented in the student handout while text in gray reflects planning information, tips, and modification options specific to the teacher's handout). We encourage the students to be placed back in their original product-specific groups if possible to play the game (Figure 1). We recommend a board for every 3 players. However, depending on the class size, a community can be represented by groups of 2-3 players instead; having more than 9 players on a single board may be difficult to manage. If there are 10 students in the class and it's consistent with the learning objectives, consider making one of the students a stand-alone banker, who is allowed to make suggestions to the communities or even, be involved as an objective third-party in the negotiation process. The game materials (product cards, chance cards, population cards, etc.) can be found in the game pieces appendix, with editable versions hosted on the SERC website, as part of the Teach the Earth collection: https://serc.carleton.edu/teachearth/activities/187653.html; the associated activity webpage on SERC also contains a video of the activity being played for reference.

[9] Kwok (2017) "Enterprise: Game On" *Nature* 547, 369–371 (20 July 2017) doi: 10.1038/nj7663-369a. Accessed at: http://www.nature.com/nature/journal/v547/n7663/full/nj7663-369a.html

[10] Susi, T., Johanesson, M. and Backlund, P. (2007) Serious Games - An Overview (Technical Report). Skövde, Sweden: University of Skövde.

[11] Full citations for these references are: 1) Kapp, K. M. (2012). The gamification of learning and instruction: game-based methods and strategies for training and education. John Wiley & Sons. and 2) Johnson, L., Adams, S., and Cummings, M.: The NMC Horizon Report: 2012 Higher education edition, Austin, Texas: The New Media Consortium, 36 pp., 2012.

[12] Medema, W., Furber, A., Adamowski, J., Zhou, Q., & Mayer, I. (2016). Exploring the Potential Impact of Serious Games on Social Learning and Stakeholder Collaborations for Transboundary Watershed Management of the St. Lawrence River Basin. Water, 8(5), 175.

Going through the game setup and reviewing the game rules takes approximately 15 minutes, although the exact time may vary depending on the students' familiarity games like Settlers of Catan™, Diplomacy™, and Risk™. The students should have the opportunity to play the game uninterrupted for at least 25 minutes. Students' behaviors in the game could be impacted by whether they can see the clock/pay attention to how much time is left for game play. So depending on the class focus/learning objectives, you may or may not want to share the explicit time allotted for game play. We recommend allotting at least 10 minutes after game play for a class debrief.

The game debrief is intended to start the reflection process for the students. After querying which communities won, ask students probing questions about their game experience. Possible questions include:

- Was there a particular reason (location, strategy, luck, etc.) that contributed to the success of a winning community?
- What was the most challenging aspect of game play?
- How often were collaborative (or consensus) development decisions made?
- If you could play the game again, would you change your strategy?
- What was one way in which the game reflected real-life? One way it didn't?
- What could planning officials learn from playing such a game?

After class, the students are assigned to write a policy brief, in which they are asked to more deeply delve into reflections on their community's development during the game. As part of this process, the students should also consider the effectiveness of their initial development strategy, whether/how the strategy was modified during game play, and any unintended consequences (including natural disasters and neighboring communities' decisions) that arose during the game. The detailed description for the policy brief assignment can be found in the Student Handout. The policy brief could either be assigned as a group assignment or individual assignment. The summative assessment associated with the policy brief can be assessed using Rubric 4.

Although some possible variations are noted on the following pages, we encourage you to modify any of the game rules to reflect the specific class/learning objectives associated with this activity. For example, if the class is sufficiently large, you could divide the class into halves, with one half explicitly informed to be cooperative with neighbors (i.e., focus on maximizing success of all communities on the board) while the other half is embodying a competitive environment (i.e., just focus on maximizing success of your community on the board). The cooperative variation could also be implemented in an additional class period. Some suggestions for incorporating pollution, climate change, tragedy of the commons, and other interesting dynamics can be found on the *Oil Springs* website:
http://www.oilsprings.catan.com/resources/#.Wam4oCiGPct

The specific scope of the written assignment can also be modified to reflect the course and level in which the lesson is implemented. For example, in engineering classes, the policy write-up could be modified to include an assessment of the role of technology in addressing challenges (such as resource constraints) observed during game play. In a modeling-oriented class, the policy brief could be replaced with the development of an Overview, Design Concepts, and Details document.[13] For classes with advanced understanding of FEW systems, the written assignment can be modified to probe assumptions made in the game design and possibly even redesign the rules. For example, you could have the students consider whether the resources needed for a given product (as stated on the development card) reflect the primary limiting factors and suggest revisions to the activity design that reflect their understanding of FEW systems.

Class 3 Breakdown:

- Setup game and review rules – 15 minutes
- Play game in product groups – 25 minutes
- Game debrief – 10 minutes
- Collect pro-con grid (pre-class assignment)
- Assign policy brief homework

Game Overview

1. You and your fellow countrymen and women have arrived in a new land that is rich in fertile soil, water, and minerals[14]. However, within this land there is no single area that is well endowed with all three of these important resources. Your goal is to settle this land and develop a prosperous and long-lived society.
2. In order to develop your community you will need to convert natural resources into products which can sustain your population. The general development flow in the game is summarized in Figure 3.

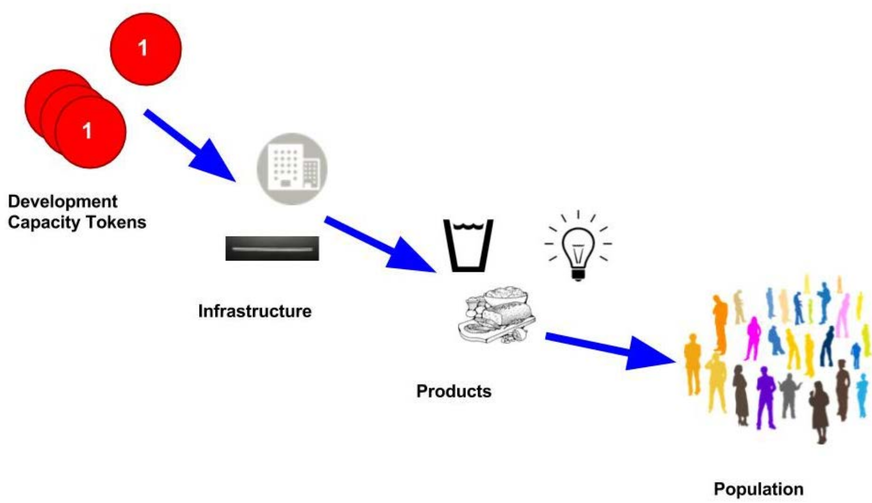

Figure 3. Development flow in game.

[13] Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., ... & Huth, A. (2006). A standard protocol for describing individual-based and agent-based models. *Ecological modelling*, *198*(1), 115-126. Accessed: http://www.sciencedirect.com/science/article/pii/S0304380006002043

[14] For simplicity, "minerals" denote a wide range of natural resources that could be used to generate electricity.

3. There are three types of landscape patches in this new land, each of which represents a natural resource. These resources are: water, fertile land, and minerals.
    a. Each resource represents the raw materials used to create the products needed to develop and maintain your community: drinking water, food, and electricity.
    b. The availability of these products determines the population that your community can support. One of each type of product (food, drinking water, and electricity) is needed to sustain one population unit.
    c. Each product card is worth one point and each population card is worth five points. **The community with the most points at the end of the game wins.**
    d. **Variation:** The goal could be altered to reflect the course learning objectives. For example, if activity is part of a lesson plan focused on how cities work together in a country, the goal could be altered to reflect collaborative decision-making: "The board with the most points (i.e., sum of all communities' points on the board) at the end of the game wins." Consider also adding "By unanimous decision you have decided to spread out and develop communities in different regions of the land" to Point #1 under the Game Overview.
4. At the beginning of the game, each player is assigned a community in a pre-specified location and five "development capacity" tokens. The "development capacity" tokens represent social, technological, and economic capabilities of your community to develop infrastructure; these tokens must be traded-in in order to build infrastructure. To develop products and increase your population you must use the tokens to develop infrastructure that transform the raw materials on the natural resource landscape patches into products and transport these products to your community location.
5. How do you acquire "development capacity" tokens?
    a. Development capacity is determined, in part, by the size of your community. Large communities have a greater workforce and economic system that can support more infrastructure projects. Therefore, at the beginning of every turn, each community receives one token per population card.
    b. In addition, as prosperity is also dependent on outside random forces, at the beginning of every turn, each community will roll a die. If the number on the die face is odd, the community collects that number of tokens. However, if a community rolls an even number, they must draw a chance card instead.
6. How do you convert resources to products?
    a. There are several prerequisites that must be met before a resource can be used to create a product for your community.
        i. Your community must be physically connected to the resource in some way. If your community touches the landscape patch on which the resource is found you are considered to be physically connected. If not, transportation infrastructure (i.e., roads) must be built along the edges of the landscape patches in order to connect your community to the resource. The roads are half the length of a resource patch.

ii. If the product requires more than one resource to be created, the landscape patches on which the resources are located must be physically connected. *For example, if no water source is found adjacent to the fertile land, water must be transported to fertile land via irrigation infrastructure in order to grow food crops.*

iii. Note that the availability of your resources is limited. Mineral and fertile land resource patches provide three units of the resource and water patches can provide up to five units. *For example, if you use a water landscape patch as input for a drinking water product card and as input for a food product card, then you can still use that same patch as input three more times.* Each unit represents the flow of resources for an indefinite period. In other words, a unit of land sufficiently supplies the nutrients needed to support 1 unit of food for 1 unit of population throughout their lives.

   1. Variation: Can incorporate environmental capacity limitations by changing the time period over which landscape patches can support populations. For example, after 3 turns, a water patch runs dry and new water resources need to be discovered.

iv. Once the physical connections between resources and your community have been made, facilities that transform the resources into the desired product must be built. *For example, before water can be used as drinking water it must be processed at a water treatment plant where it is transformed to remove bacterial and other contaminants into the relatively clean and sterile water that comes out of our faucets.* Each facility is capable of transforming one unit of a resource into one unit of the desired product.

v. The cost of building facilities used to transform resources into products is 1 token for each unit developed on a patch.

   1. Groundwater Variation: The cost of building facilities increases to 3 tokens for the 4th and 5th resource units developed on water patches. *For example, once all of the easily accessible surface water in an area has been allocated, communities may drill wells to access groundwater, however access to this groundwater comes at an additional cost.*
   2. Transport Variation: For each facility built on resource patches distant from your community (e.g., more than 3 patches away), an additional one-time payment of 1 token must be made to cover shipping costs.

vi. Your development card summarizes the resources, infrastructure, and associated tokens needed to develop products.

7. How do you utilize products to increase your population?
   a. A set of one food, one drinking water, and one electricity card can be traded in for one population card during any round of game play.
   b. If, for any reason, you do not have enough products to sustain your current population, any unsupported population cards must be turned over (rendered inactive) until your product supply is replenished. *For example, if a chance card requires you to turn in 1*

drinking water card but you do not have any in your hand, then you need to turn over one of your population cards until you are able to turn in a drinking water card.

   c. You may decide during any round to turn back in a population card for a set of product cards.

8. What if I don't have all the resources I need to grow my population?
   a. You can trade and negotiate with other communities so long as your communities are connected by infrastructure. You may trade resources, products, tokens, or favors. There are no specific rules limiting possible trades and negotiations. Use your imagination!
9. Carefully consider how to balance your population growth with your development. Chance cards may produce unexpected results!

Game Rules

These pages include all the information you need to play the game. For specifics on developing your resources during game play, you may refer to the Development Card.

1. Landscape patches are considered naturally connected if they share an edge (no diagonal connections) and communities are considered connected to all landscape patches they touch.
2. In order to collect a product card, the necessary resources must be connected (either directly or through infrastructure) and transformed. The development card lists the resources and infrastructure needed to develop each of the products.
   a. In order to produce 1 unit of drinking water, a community must be connected to a water resource patch containing both 1 available resource unit and 1 facility.
   b. In order to produce 1 unit of food, a community must be connected to a fertile land patch and a water patch that both have at least 1 available resource unit as well as a facility on the fertile land patch. The associated water patch must be connected (either directly or through infrastructure) to the fertile land patch on which the food is being produced. Note that the patch with the production facility must also be physically connected to your community.
   c. In order to produce electricity, a community must be connected to a mineral patch and a water patch that both have at least 1 available resource unit as well as a facility on the mineral patch. Again, the associated water patch must be connected (either directly or through infrastructure) to the mineral patch on which the electricity is being produced, and the patch with the production facility must be physically connected to your community.
3. There are 3 resource units per mineral and fertile land patches and 5 resource units per water patch. The quantity of resources used by communities should be indicated on each landscape patch using hash marks.
4. Roads can be used to connect communities with resources. Roads are half the length of a landscape patch edge and extend along edges of landscape patches connecting at midpoints (see board example in Figure 4). Roads must be connected to your community or to other road segments (i.e., no free-floating roads). Communities are able to utilize resources at patches touching the sides of a road. Each road segment costs 1 token.

5. Facilities should be placed on the associated primary resource landscape patch: a drinking water facility is on a water patch, a food facility on a land patch, and an electricity facility on a mineral patch. One facility is needed to per one unit of product. Multiple facilities may reside on the same patch. Each facility costs 1 token.
    a. Groundwater Variation: Facilities placed on water patches to access the 4th and 5th resource units cost 3 tokens each.
    b. Transport Variations:
        i. If a facility is placed on a patch more than 3 patches away from your community, an additional 1 token must be paid to account for shipping costs.
        ii. A player may pay 2 tokens to place a roadblock on any road segment (within 2 patches of their community) in order to prevent other players from using the road to access patches.
6. A set consisting one of each product card (i.e., 1 drinking water, 1 food, and 1 electricity card) is required to obtain 1 population card.
7. Trades and negotiations may be conducted between any players during any round of the game after setup has been completed.
8. Chance cards may benefit or injure a community's development. Once drawn, the community cannot make any development decisions (including building infrastructure) unless it is directly related to meeting the criteria on the Chance Card. If an immediate resolution is not available to the community, they have the following options:
    a. Turn over a population card (i.e., render it "inactive") to continue making development decisions. The population card can become active again once the criterion on the Chance Card has been satisfied.
    b. Turn back in a population card for each of the individual product cards.
    c. Enlist assistance from one of their neighbors for assistance.
    d. Hold onto the Chance Card until the next turn and hope they gain some tokens that will help get them out of their rut.

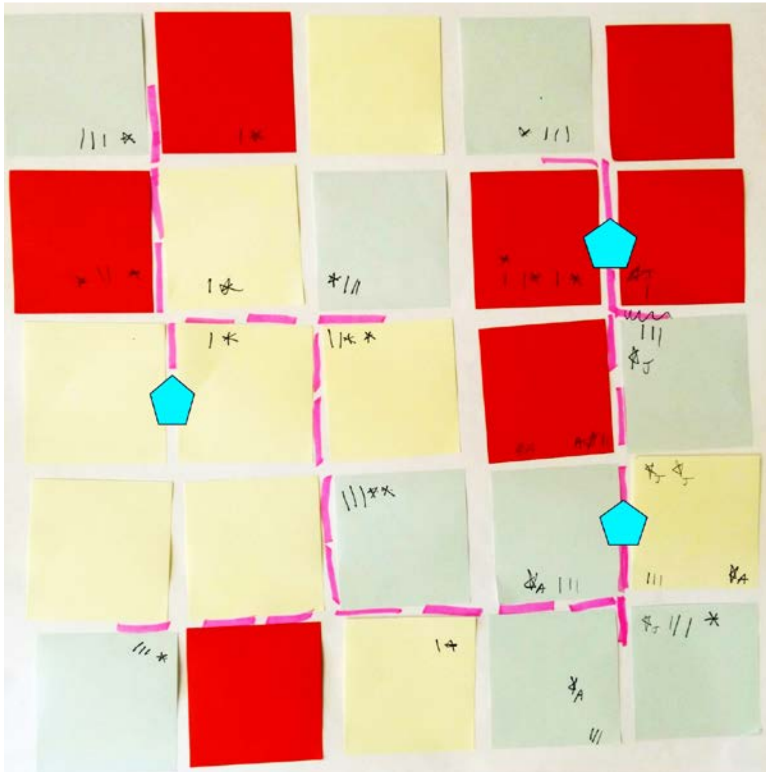

Figure 4. Example of a game board layout. Community locations (teal pentagons), marked road segments (pink highlighter), resource unit utilized (hash marks), and facilities developed (stars).

Materials (provided by teacher)

- Game board with 3 resource patches (water, fertile land, minerals) marked
    - Materials: The game board can be created on any flat surface using a large piece of paper and 3 sets of colored post-it notes laid out in a 5 by 5 pattern (see example layout in Figure 4); different colors can be substituted if blue, green, and orange color notes are not available. Or if resources are available, the board layout could be created in PowerPoint and printed ahead of time (see SERC website).
    - Variation: The base model contains 9 patches of water, 8 patches of land, and 8 patches of minerals. These numbers can be changed to reflect the class focus/learning objectives associated with the activity. There are also a lot of ways the landscape patches could be laid out. So feel free to modify this aspect of the game as well.
- Community markers
    - Materials: Mark three community locations on each board. The community locations can either be drawn directly on the board or be marked using metal game pieces from a Monopoly set or settlement structures from a Settlers of Catan set.
    - Variation: For the base model, the communities should be placed on the edge of a landscape patch (i.e., not on a corner). However, this could be modified. The location of the communities relative to resource patches could also be modified to reflect the specific class focus in which this activity is used.
- Product cards (3 types)

    - Materials: Prepare 3 stacks of product cards: drinking water, food, and electricity. We recommend having at least 12 cards of each product type per game board. See appendix for sample cards that could be printed and cut; the SERC website contains editable materials. Or you could just write the product names on a set of post-its (preferably different color than those used for landscape patches).
- Development cards ("W" - water, "L" - fertile land, "M" - minerals)
    - Materials: We recommend providing one development card per player. See appendix for sample cards that could be printed and cut; the SERC website contains editable materials. We recommend making sure that the colors used for the landscape patches are consistent with the colors used on the game board if possible. Alternatively, you could write down the necessary information on the board.
- Population cards
    - Materials: We recommend having at least 15 population cards per game board. See appendix for sample cards that could be printed and cut; the SERC website contains editable materials. Alternatively, you could use a different colored post-it note and label accordingly.
- Chance cards
    - Materials: You need one set of chance cards per game board. See appendix for sample cards that could be printed and cut; the SERC website contains editable materials.
    - Variation: Depending on the class focus, you could create different or additional chance cards to influence game behavior (e.g., A torrential downpour occurs and you lose all food facilities on a particular patch, which need to be replaced by a token per facility).
- Infrastructure pieces (roads and facilities)
    - Materials: We recommend having at least 20 road pieces and 20 facilities per game board. These pieces can be sourced from a Settlers of Catan™, substituted with Lego pieces, or constructed from craft materials (such as pipe cleaners or skinny post-it notes). Alternatively, roads and facilities can be drawn directly on the landscape patches with a sharpie.
- Tokens
    - Materials: We recommend having at least 30 tokens per game board. Various craft materials can serve as tokens, including buttons or bingo chips.
- Dice
    - Materials: You need one die per game board. You could either borrow them from another game or purchase them from a retail store (search for "Dice Game")
- Sharpie
    - Used to mark the number of resource units utilized on each landscape patch

Note: Although all of the game cards can be printed in B&W, we recommend printing them in color if possible. If you have multiple class sections in which students will play the game, consider laminating some of the materials or printing the cards on cardstock for durability purposes.

Setup

(Approximately 15 minutes, could be less depending on students' experience with similar games like Settlers of Catan™)

1. Setup the game board with resources and community markers.
    a. To reduce overall time needed, we recommend setting up the game board before the start of class; it takes approximately 5 minutes to setup the post-it note board.
2. Assign each player a community to act on behalf of.
    a. We recommend a board for every 3 players. However, depending on the class size, a community can be represented by groups of 2-3 players instead. Having more than 9 players on a single board can get overwhelming to manage. If there are 10 students in the class and it's consistent with the learning objectives, consider making one of the students a stand-alone banker, who is allowed to make suggestions to the communities or even, be involved in the negotiation process.
3. Assign each player a role.
    a. We recommend assigning one student to be the Banker (responsible for distributing tokens and cards), one student to be the Record-keeper (responsible for marking construction of roads, facilities, and use of resource units on the game board), and one student to be the Enforcer (responsible for making sure the Game Rules and Game Play steps are being followed).
4. Each community collects 5 tokens to start.
    a. Variation: If the class focus is on environmental justice considerations, consider having communities start with different numbers of tokens. You could also modify the die roll rules (e.g., one of the communities routinely gets one less token than the odd number they roll).
5. Determine order of play: Each community takes a turn rolling the die. The community with the largest value begins, with the game play continuing to the left.
6. Establish communities: Following the established order of play, each community makes their initial development decisions, following Game Rules 1-7. Be sure to mark the quantity of resource units used and infrastructure developed as well as collect any associated product and population cards.
    a. Variation: The specific timing of the initial development could be varied. For example, it could occur as part of Round 1 to reflect that different cities develop at different times.

Game Play

(Approximately 6 minutes per round)

Game play begins immediately after setup has been completed. Each round of game play is turn-based, following the established order of play. During their turn in each round a community will undertake the following steps:

1. Community collects 1 token for each active population card
2. Community rolls the die
    a. If an odd number is rolled, the community collects the associated number of tokens

   b. If an even number is rolled, they draw a Chance Card and follow the directions printed on the card.
      i. Remember if you do not have enough cards or tokens in your hands, or enough product facilities in play, to follow the Chance directions, then you must turn over (render inactive) as many population cards as necessary to address the product deficit. If that option isn't available, you can ask your neighbors for aid or hope that your next turn/die roll brings you tokens.
      ii. A community can decide at this point to turn in an existing product card in order to free up a utilized resource unit for another purpose or to turn in a population card for a set of product cards.
      iii. Once the chance card has been fulfilled, it should be returned to the bottom of the chance card deck.
3. Community makes development decisions, following Game Rules 1-7.
   a. Be sure to mark the quantity of resources used and infrastructure developed, collect any associated product cards, and trade in product cards for the desired number of population cards.
   b. During this time, the community may negotiate agreements with other communities and trade for resources, products, or tokens.
      i. Variation: Depending on specific learning goals (e.g., collaborative policymaking), the rules and timing of negotiations could be modified. For example, this step could be moved to "Game Rule 5" after all of the cities rolled the die so that rather than negotiating during their individual turn, the communities are forced to negotiate together at the same time. Note: communal negotiations take longer, adding approximately 3 minutes to the length of each round.
4. Repeat steps 1-3 for each community
5. Repeat steps 1-4 until the end of the game
6. End of Game
   a. When time is up, each community tallies their points. The community with the most points wins!
   b. Remember
      i. Each product card is worth 1 point
      ii. Each active population card is worth 5 points

Rubric #4: Policy brief

Criteria	**5**	**3**	**1**	**Points Awarded**
Initial Strategy Evaluation: Were the strategy's strengths and weaknesses discussed in the context of community resiliency? Were insights from the game drawn to inform these considerations?	Both strengths and weaknesses were discussed in the context of community resilience. Insights from game play are obvious.	Some strengths and weaknesses discussed; unclear about connection to community resilience and game play.	Unclear how points connect to strategy assessment or game play.	
External factors: Were "out of control" factors discussed in the brief? Were unintended consequences of community's strategy mentioned?	Both "out of control" factors and unintended consequences were addressed	Only one set ("out of factors" or unintended consequences) addressed	Neither set was addressed	
Modifications: Were strategy modifications proposed? If no, was there was a justification provided?	Proposed modifications reflect initial strategy evaluation and external factors	Proposed modifications exist but unclear how they reflect game play	No proposed modifications	
Critical and Systems Thinking: Does student demonstrate evidence of critical thinking skills and systems thinking skills?	Student demonstrates excellent ability to connect FEW concepts and factors related to community resilience strategies	Student demonstrates good ability to connect FEW concepts and factors related to community resilience strategies	Student demonstrates poor ability to connect FEW concepts and factors related to community resilience strategies	
Communication: Is the writing easy to follow and understand? Does the style and organization enhance reader comprehension?	Writing style is clear and well-organized, thus facilitating reader comprehension	Main points are there but writing style is only somewhat clear and organized	Unclear what the sentences mean or how they relate to each other	
			Total points (out of 25)	

Detailed feedback/critique:

5. Appendices

A. Background Information

Water

Water is integral to all facets of our lives. Not only is water important for our consumption, it is also an integral component of food production (growing crops)[15], electricity production (for hydropower generation and meeting cooling needs at thermoelectric plants)[16], and transportation sectors (shipping for example). Water can also be used for a variety of recreational purposes, including boating, fishing, and swimming. Additionally, water can be embedded in the cultural identity for many groups. For example, many religious practices (including Baptism and Hindus' bathing in Ganges River) are connected to water[17].

Although our Earth is mostly made up of water, only about 3% of all water is fresh.[18] This freshwater is mostly tied up in glaciers and ice caps or permafrost, leaving only a small percentage of total water that is actually accessible for our needs. Water can be sourced a number of ways, including locally, through rainwater collection and groundwater extraction and from afar, with canals or pipelines redistributing the resource.[19] With increasing global trade, water can also be transferred in a virtual form (i.e., the water embedded in a product, such as a pound of cotton) has also emerged as a way to transfer water between regions.[20]

Most ancient civilizations prioritized water availability when citing their settlements. In fact, many considered controlling water sources was a critical aspect of security.[21] In modern society, water use for a particular purpose is often dictated by supply and quality constraints. While ships can travel across oceans, we cannot drink saline water directly. In fact, a lot of freshwater that we typically source is subject to various contaminants that need to be removed before it is fit for our consumption. Globally,

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[15]The agriculture sector accounts for the majority of water use, both globally (http://www.fao.org/nr/Water/aquastat/water_use/index.stm) and domestically (https://www.ers.usda.gov/topics/farm-practices-management/irrigation-water-use/)

[16] National Geographic provides a few resources regarding the role of water in generating electricity: https://www.nationalgeographic.org/activity/role-water-generation-electricity/

[17] In his book "Troubled Waters: Religion, Ethics, and the Global Water Crisis," Chamberlain examines the central role of water in various traditions and rituals: https://books.google.com/books?id=oAHhdczi9CcC

[18] Visit the USGS website for an overview of the hydrologic cycle and distribution of freshwater resources: https://water.usgs.gov/edu/watercycle.html

[19] In many developing societies, water is collected and transported by household members, often females: http://www.un.org/waterforlifedecade/gender.shtml

[20]More details about the magnitude of the virtual water trade can be found here: http://waterfootprint.org/en/water-footprint/national-water-footprint/virtual-water-trade/. The water footprint network contains various resources to explore the footprints of regions as well as for students to calculate their personal water footprint: http://waterfootprint.org/en/resources/

[21] In 1901, French General Hubert Lyautey noted that "He who controls the water controls the population."

780 million do not have access to an improved drinking water source.[22] The level of treatment necessary is often dependent on the upstream sources that influence the water quality. In cities, for example, water is typically collected and treated at a water treatment plant prior to distribution to households. Most water treatment plants in the US subject the water to some level of filtration and disinfection[23] to improve its quality so that it meets the drinking water standards set by the EPA. Every community water supplier must provide an annual "Consumer Confidence Report" to its customers summarizing their water source and results of quality tests.[24]

In many rural areas, however, residents often source their drinking water from private wells. These households are recommended to test their drinking water sources to make sure they meet safety standards. Generally, groundwater is assumed to have higher water quality than surface water since the former benefits from filtering properties of soils. However, households often do some level of treatment (e.g., reverse osmosis) to ensure they are consuming water of good quality. Since you don't necessarily need drinking quality-level to water lawns or wash cars, some rural households in the US as well as cities in other countries distinguish between potable and grey water use in their houses, where potable water is subject to treatment while grey water is sourced directly from rainfall or reused water from showers.

After being used, water - now in the form of wastewater - needs to be managed in some way to reduce sanitation issues. Unfortunately, there are 2.5 billion people in the world that lack access to improved sanitation facilities.[25] When they are managed, decisions regarding level of treatment for wastewater depend on local resources and what the water was used initially for. Typically, wastewater from urban spaces in the US is collected for treatment at a wastewater treatment plant prior to being released to the environment.[26] Rural households often have septic systems that collect solid wastes and depending on the system capacity and design, are emptied periodically for disposal. Often, our decisions depend on ecosystem services to some degree for dilution. For example, most wastewater treatment plants do not treat for chemicals that are introduced into the water streams from our pharmaceuticals and personal care products. Water used for thermoelectric cooling, for example, is often warmer downstream of the plant than upstream and depends on the dilution capacity of the releasing water body to dissipate some

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[22] An improved drinking water source protects water from contamination sources. Examples included here: https://www.unicef.org/wcaro/overview_2570.html

[23] Summary of common processes involved in community water treatment plants: https://www.cdc.gov/healthywater/drinking/public/water_treatment.html.

[24] Local Consumer Confidence Reports can be explored using the EPA website: https://ofmpub.epa.gov/apex/safewater/f?p=136:102

[25] Diarrheal disease is the second leading cause of death for children under five globally: http://www.who.int/mediacentre/factsheets/fs330/en/. These deaths can be prevented by increasing access to improved sanitation facilities, which ensure hygienic separation between excreta and human contact. Examples are presented here: https://www.unicef.org/wcaro/overview_2570.html

[26] The wastewater treatment process is somewhat similar to water treatment, since it also involves removal of solids and disinfection. Although there are a lot of variations in the specific set-up, this animated graphic summarizes the main processes: http://www.sheffy6marketing.com/index.php?page=test-child-page

of the excessive heat. Increasingly, wastewater is being recognized as valuable resource of raw materials.[27]

As indicated above, water is influenced by both natural forces and social forces. The hydrological cycle is inherently a physical process, driven by solar and gravitational energies. Climate change is expected to influence a large number of water processes by increasing temperatures and altering the distribution of water availability.[28] Concurrently, human processes can also influence water. From building dams and canals to setting water quality standards, we can also alter water processes. New technologies (e.g., desalination) and policy[29] changes mean that our associations with water over time are also subject to change. For example, environmental flows (i.e., water needed to sustain local ecosystems) are becoming increasingly valued since local ecosystems need this water to survive and also, provide us with other services (e.g., clean air from forests). There is a growing concern about drinking water quality issues in the US, especially with events in Flint, MI and increased understanding of arsenic levels in our water.[30] Thus, most management studies consider water to be part of socio-ecological system[31] and underscore the importance of understanding both the natural and social factors influencing water.

Food

Food is an important source of energy that all species need to grow and survive. Food for human consumption can occur in various forms, which all serve as sources of nutrition. Generally, an individual's diet consists of some portion of grain, produce, dairy & eggs, meat, and sugar & fats.[32] Food can be scavenged from nature, grown in household farms at a subsistence level, or produced at a commercial-scale. The total level of resources required for any type of food depends on a number of factors, including how it is sourced/grown, processed, and transported prior to consumption.

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[27] On World Water Day, UN said that wastewater should be recognized as a valuable resource: http://www.un.org/apps/news/story.asp?NewsID=56397#.WZ-DCSh97IU

[28] Summary of climate change impacts on the US water sector: http://nca2014.globalchange.gov/highlights/report-findings/water-supply

[29] There are numerous federal policies that influence water dynamics in the US, including the Clean Water Act, Safe Drinking Water Act, etc. More info here: https://www.epa.gov/regulatory-information-topic/regulatory-information-topic-water. Some states and local governments have additional policies and laws that influence water management. Researchers are also exploring economic frameworks to improve water management practices: Tricas, Marisa, and Barry Liner. "A framework for improving economic analysis of water reuse opportunities." *International Journal of Environmental Policy and Decision Making* 2.3 (2017): 207-220.

[30] USA Today recently summarized recent water issues: https://www.usatoday.com/story/news/2017/08/14/63-million-americans-exposed-unsafe-drinking-water/564278001/

[31] Cabello Villarejo, Violeta, et al. "River basins as socio-ecological systems: linking levels of societal and ecosystem metabolism in a Mediterranean watershed." *Ecology and Society* 20.3 (2015). Accessed online at: https://www.ecologyandsociety.org/vol20/iss3/art20/

[32] There is a lot of variation in national dietary profiles, many of which can be explored here: http://www.nationalgeographic.com/what-the-world-eats/

Food is heavily influenced by cultural norms and religious beliefs, leading to various dietary styles throughout the world. Certain diets are defined by the inclusion or exclusion of certain foods (e.g., veganism, vegetarianism, and pescetarianism) while others are influenced by the food preparation styles (e.g., Kosher and Halal). Some national cuisines are characterized by certain flavor profiles (e.g., masala in Indian cuisine, coconut in Thai cuisine, and chilies in Mexican cuisine). Certain diets like the Mediterranean diet, which is characterized by high consumption of vegetables, olive oil, and moderate consumption of protein, were labeled relatively early as one of the healthiest diets.[33] However, the nutritious quality of our current diet compared to our bodies' requirements has long been an active area of research.[34]

In addition to cultural norms, our consumption habits are influenced by our individual preferences and tolerances (e.g., allergies) as well as food availability and affordability.[35] Global trade for agricultural products has steadily increased over time,[36] increasing the availability of certain foods at relatively stable prices year-round. However, global trade[37] has also increased the impact of "fad" diets on local systems that produce certain staple foods (e.g., avocados) such that they are no longer affordable to the farmers that grow them.[38] In the US, fresh foods may be harder to access than their processed counterparts (e.g., potatoes vs. potato chips) leading to high prevalence of food deserts, especially in rural areas.[39]

The primary inputs for food production are generally: land, water, solar energy, and nutrients; increasingly, energy has also become an important input for operating machinery/manufacturing fertilizers. Approximately 10% of land is actually arable (i.e., can be ploughed to grow crops) and it is not

[33] Willett, Walter C., et al. "Mediterranean diet pyramid: a cultural model for healthy eating." *The American journal of clinical nutrition* 61.6 (1995): 1402S-1406S.

[34] Unfortunately, the research process is not immune to conflicts of interest: http://www.npr.org/sections/thetwo-way/2016/09/13/493739074/50-years-ago-sugar-industry-quietly-paid-scientists-to-point-blame-at-fat

[35] The FAOSTAT database provides an overview of various food and agriculture metrics (including availability, accessibility, affordability, and utilization) for over 245 countries and territories throughout the globe: http://www.fao.org/faostat/en/

[36] Anderson (2010) "Globalization's effects on world agricultural trade, 1960–2050" *Philos Trans R Soc Lond B Biol Sci.* 365(1554): 3007–3021. Doi: 10.1098/rstb.2010.0131. Accessed at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2935114/

[37] A framework for exploring impacts of global trade on food security was developed by: Suweis, S., Carr, J. A., Maritan, A., Rinaldo, A., & D'Odorico, P. (2015). Resilience and reactivity of global food security. *Proceedings of the National Academy of Sciences*, *112*(22), 6902-6907. http://www.pnas.org/content/112/22/6902.full?sid=d75de1ae-408d-4015-87a1-8854b968f9a7

[38] Read more here: https://www.theguardian.com/lifeandstyle/2017/aug/06/mexico-considers-importing-avocados-as-global-demand-drives-up-prices

[39] Map of US food deserts can be found here: http://americannutritionassociation.org/newsletter/usda-defines-food-deserts

evenly distributed globally.[40] The agriculture sector accounts for the majority of water use, both domestically (80%) and globally (70%). The water used for growing food can come in various forms, from rainfall falling directly onto farm fields to surface water redirected using canals and groundwater pumped from underground. The quality of these water sources often varies depending on upstream users, with untreated or partially treated wastewater often being used in irrigated agriculture and aquaculture.[41] Agriculture and aquaculture can be intertwined on the same land, such as in aquaponics systems and in rice-fish fields.[42] The benefits and tradeoffs of wastewater as an input are still an active area of research, since wastewater can be a source of nutrients but certain contents (e.g., metals) can also cause a public health concern. In urban spaces, water from the tap that is used to grow food is typically treated to a drinking water quality, which requires a certain amount of energy and water investments. In the US, a lot of livestock production occurs in concentrated animal feeding operations (CAFOs), which has raised concerns about water and associated air quality.[43] Nutrient pollution, in general, is a significant issue facing the agriculture industry, since it contributes to the development of algal blooms, which leads to dead zones and fishkills.[44] Programs such as water quality trading programs[45] and growing awareness of the value of "organic" and "natural" foods draw attention to the conditions under which food was grown/raised.

The energy investments associated with growing food are not insignificant, accounting for 3% of total energy consumption. Fertilizer production is estimated to account for half of those energy needs.[46] Most foods are also transported long distances, burning a lot of fossil fuels in the process.[47] Some movements

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[40] Information on global and national trends of arable land can be found here: http://data.worldbank.org/indicator/AG.LND.ARBL.ZS

[41] Thebo et al (2017) estimate "that 65% (35.9 Mha) of downstream irrigated croplands were located in catchments with high levels of dependence on urban wastewater flows. These same catchments were home to 1.37 billion urban residents. Of these croplands, 29.3 Mha were located in countries with low levels of wastewater treatment and home to 885 million urban residents." More information can be found here: Thebo, A. L., Drechsel, P., Lambin, E. F., & Nelson, K. L. (2017). A global, spatially-explicit assessment of irrigated croplands influenced by urban wastewater flows. *Environmental Research Letters*, *12*(7). Accessible free online at: http://iopscience.iop.org/article/10.1088/1748-9326/aa75d1/meta

[42] More info about such type of systems can be found here: http://www.knowledgebank.irri.org/training/fact-sheets/crop-establishment/item/rice-fish-systems-fact-sheet

[43] Globally, methane emissions from livestock account for 15% of all anthropogenic greenhouse gas emissions: http://www.fao.org/news/story/en/item/197623/icode/

[44] A prominent dead zone is in the Gulf of Mexico, which suffers from high nutrient loads in the Mississippi: https://www.epa.gov/nutrientpollution/effects-dead-zones-and-harmful-algal-blooms

[45] Most of these programs tend to be voluntary but there are multiple federal and local policies that govern agriculture production. The USDA is a good place to start to understanding some of these laws: https://www.usda.gov/our-agency/about-usda/laws-and-regulations

[46] A great summary of energy use in food production can be found in Woods et al (2010): https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2935130/

[47] In 1998, produce transported to Chicago by trucks traveled over 1500 miles from their origin: http://ngfn.org/resources/ngfn-database/knowledge/food_mil.pdf

such as farm-to-fork and farmers' markets aim to counter these issues. During transportation, most food is either chilled or frozen for preservation purposes, which require another set of energy investments. Certain foods are further processed (e.g., canned and dried or made into new foods altogether, like cereal) prior to being transported to consumers. Except for some fruits and vegetables, we rarely eat food in its raw form in the US. So there are energy investments associated with food preparation as well. When food is cooked over wood, charcoal, natural gas, or an electric stove, more energy is invested in the process.[48] Certain crops are also directly used an inputs for bio-based fuel production; in 2012, corn-based starches were used to produce 94% of biofuel production in the country, with the rest coming from soy oil, waste oil, and grease.[49]

Roughly a third of the food we produce globally is wasted, with losses occurring at various stages.[50] In 2010, for example, approximately 31% of available food supply in the US (equaling 133 billion pounds of food) was wasted at the consumer- or retail- levels. Decomposition of all this organic matter in the landfill releases gas, which has high methane content and thus, higher global warming potential than carbon dioxide. Fortunately, there are numerous efforts underway to reduce food waste generation in the US, by identifying opportunities to donate, repurpose, and compost.[51] There are also initiatives to capture landfill gas for electricity generation; 634 landfill gas energy projects were in operation as of June 2017.[52]

As indicated above, there are various natural and social factors that influence food. While we continue to strive to provide healthy food to all,[53] some pressures on the horizon for food systems include: climate change, population growth, and changing diets.[54] Climate change is expected to influence food production in various ways, including warmer temperatures, increasing variability of precipitation, and increasing pest exposures. Although CO_2 fertilization may improve yields of certain crops, climate change is generally expected to adversely impact global food security.[55] In addition to climate change,

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[48] In many cultures, women bear the primary burden of preparing food for household consumption.
[49] Latest stats can be found on the USDA website: https://www.ers.usda.gov/data-products/us-bioenergy-statistics/us-bioenergy-statistics/
[50] Post-consumer waste rates are much higher in the developed world: http://www.fao.org/save-food/resources/keyfindings/en/
[51] For example, see Nashville's efforts to reduce food waste: https://www.nrdc.org/sites/default/files/nashville-food-waste-initiative-fs.pdf. USDA hosts resources regarding conducting audits: https://www.usda.gov/oce/foodwaste/Challenge/index.htm
[52] More information about current landfill gas projects can be found here: https://www.epa.gov/lmop/landfill-gas-energy-project-data-and-landfill-technical-data
[53] Both acute (e.g., Yemen: http://www1.wfp.org/yemen-emergency) and chronic crises still persist. More than 2 billion people still suffer from malnourishment: https://www.theguardian.com/global-development/2014/oct/13/hidden-hunger-food-access-malnutrition
[54] This list could be appended by numerous factors, including soil degradation: Lal, R. (2003). Soil erosion and the global carbon budget. *Environment international*, *29*(4), 437-450.
[55] Wheeler and von Braun (2013) "Climate Change Impacts on Global Food Security" *Science* 341: 6145, pp. 508-513, DOI: 10.1126/science.1239402, Accessed: http://science.sciencemag.org/content/341/6145/508

overall increasing demand for food to meet population growth is increasing pressures on our food systems. Fortunately, growing awareness and numerous programs, including technological developments that reduce resource requirements (e.g., drip irrigation technology) [56] are increasing the resiliency of our food systems to these growing pressures.

Energy

We use energy whenever we turn on lights, warm homes, or drive our cars. Energy is generally defined as the ability to do work.[57] There are generally two basic categories (potential energy and kinetic energy)[58] that can occur in various forms, including chemical, mechanical, nuclear, gravitational, thermal, and electrical. We have been able to harness these various forms to provide heat and other resources needed to sustain our societies. Our ability to transfer energy from one state to another (e.g., using energy embedded in moving water to generate electricity) is strongly governed by the law of conservation, which states that energy can neither be created nor destroyed, just altered from one form to another.

Historically, our societies predominantly relied on converting chemical energy in either solid form (e.g., biomass and coal) or in fluid form (e.g., petroleum and natural gas) into thermal energy to meet our needs; the long history of interactions between humans and fire have been traced back to 2 million years ago.[59] Archaeologists have found evidence of coal use by Romans in England as far back as 100 AD but coal use mainly expanded during the Industrial Revolution, after it was discovered that coal-based fires burned cleaner and hotter than wood charcoal. Coal-based electricity generation began in 1880s but most homes still used furnaces (fueled with charcoal or coke) for heating. Today, electricity is generated from a combination of chemical energy sources as well as nuclear, gravitational, radiant, and motion energy sources.[60] Depending on the source, energy generation requires investments at various stages (including extraction, processing, transportation, and distribution), each of which bears its own land[61] and water[62] footprints. Future projections of fuel distribution generally indicate that the largest

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[56] Look at some of the incredible achievements being made by Netherlands in this regard: http://www.nationalgeographic.com/magazine/2017/09/holland-agriculture-sustainable-farming/

[57] Although food is the primary way we as humans obtain energy, in the context of FEW systems, we typically refer to energy as resources needed to sustain our communities.

[58] More information about energy forms can be found here: https://www.eia.gov/KIDS/energy.cfm?page=about_forms_of_energy-basics

[59] Gowlett, J. A. (2016). The discovery of fire by humans: a long and convoluted process. *Phil. Trans. R. Soc. B*, *371*(1696), 20150164. Accessed at: http://rstb.royalsocietypublishing.org/content/371/1696/20150164

[60] The overall portfolio of fuel shares globally didn't change much between 1970s and 2010s, except for nuclear energy and natural gas replacing some of the oil shares. More information about the total world share of fuel consumption and supply as well as OECD breakdowns can be found here: https://www.iea.org/publications/freepublications/publication/KeyWorld2016.pdf

[61] Nuclear energy had the highest energy density from a land perspective while biofuels the least: Cheng, V. K., & Hammond, G. P. (2017). Life-cycle energy densities and land-take requirements of various power generators: A UK perspective. *Journal of the Energy Institute*, *90*(2), 201-213. Accessed: http://www.sciencedirect.com/science/article/pii/S1743967115300921

momentum for energy sources lie in natural gas and renewables.[63] Renewable energy refer to energy that is collected from natural resources that are replenished on a human timescale, such as sunlight, wind, waves, and geothermal heat. So although nuclear energy is does not emit carbon like fossil fuels do, it is also non-renewable.

Growing interest in renewable energies is primarily driven by increased understanding of the adverse impacts of combustible fuels. The energy sector (which are primarily driven by fossil fuels such as coal and natural gas) is the leading contributor to global[64] and US[65] greenhouse gas emissions. Thermoelectric-based cooling also requires a significant amount of water resources to transport waste heat from the system, accounting for approximately 40% of total freshwater use in the US.[66] Additionally, burning biomass and fossil fuels can release a lot of particulates, which can be harmful to our health.[67] Waste management issues associated with combustion residues[68] and high-level radioactive waste[69] from coal-based and nuclear-based energy generation as well as earthquakes from disposal of natural gas-derived produced water[70] is also problematic. Renewables, on the other hand, are expected to pose relatively lower environmental and public health burdens.[71] Another advantage of renewables is that they generally require a lot less water to operate and they can be generated by various users, which has important developmental and security[72] implications from a decentralized grid perspective. For example, it is hard to layout standard electric lines (connected to coal-fired and natural-

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[62] Understandably, the water footprints for hydropower and biomass dominate across fuel sources: Mekonnen, M. M., Gerbens-Leenes, P. W., & Hoekstra, A. Y. (2015). The consumptive water footprint of electricity and heat: a global assessment. *Environmental Science: Water Research & Technology*, *1*(3), 285-297. Accessed: http://waterfootprint.org/media/downloads/Mekonnen-et-al-2015.pdf

[63] Refer to Figure 1-5 World energy consumption by energy source: https://www.eia.gov/outlooks/ieo/world.php

[64] https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data

[65] https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

[66] More information here: https://water.usgs.gov/edu/wupt.html

[67] Reliance on inefficient cook stoves and fuels actually poses a disproportionate burden of women and children worldwide: http://cleancookstoves.org/impact-areas/women/

[68] Issues facing towns storing coal ash: http://www.npr.org/2016/07/05/484316989/communities-uneasy-as-utilities-look-for-places-to-store-coal-ash

[69] No long-term storage plan for high-level radioactive waste has been developed: http://www.world-nuclear.org/nuclear-basics/what-are-nuclear-wastes.aspx. Additionally, concerns over incidents such as Fukushima strongly influence perceptions of hazards associated with nuclear energy: http://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/fukushima-accident.aspx

[70] Research shows that increases in wastewater pumping underground coincided with Oklahoma's rising number of earthquakes: Walsh, F. Rall, and Mark D. Zoback. "Oklahoma's recent earthquakes and saltwater disposal." *Science advances* 1.5 (2015): e1500195. Accessed at: http://advances.sciencemag.org/content/1/5/e1500195.short

[71] Jacobson, M. Z. (2009). Review of solutions to global warming, air pollution, and energy security. *Energy & Environmental Science*, *2*(2), 148-173.

[72] Read more about cascading impacts of blackouts and the dangers they pose here: Amin, M. and Schewe, P (2017) "Preventing Blackouts: Building a Smarter Power Grid" https://www.scientificamerican.com/article/preventing-blackouts-power-grid/

gas fired power plants) in countries with rugged terrains like Nepal. So generating electricity locally using solar energy becomes extremely beneficial; in fact, all remote airports and telecommunication facilities are powered using solar energy in the country.[73] However, we should be cautious about using a broad brush to classify all renewable energy mechanisms as having only positive impacts. Large-scale hydropower generation, for example, can severely impact fish biodiversity.[74] Similarly, using agricultural land to generate biofuel crops can have significant local impacts on grasslands, wetlands, and success of apiaries.[75]

Social factors influencing energy needs are population growth, changing habits (e.g., proliferation of smartphones and internet use), and utility markets[76] to name a few. Fortunately, our energy issues are being addressed both from a supply and demand perspective. For example, innovative technologies are looking to modify behavior at the household level.[77] Concurrently, we are expanding our energy harnessing capabilities to algal- and wave-based energy forms as well. Some entities are also exploring human-derived energy as well, from using bikes to power facilities[78] to developing textiles that harness our body movements to power our gadgets.[79] Improved battery technologies are also helping to revolutionize the energy sector by increasing our storage capacity, which would offset lulls in solar or wind energy availabilities, and allow our electric cars to travel farther on a single charge.[80] We are also increasing our abilities to harness energy from biowaste, such as landfill gas (see previous section on food) and human waste. For example, a Kenyan company is combining human waste and sawdust to manufacture briquettes, as a healthier fuel alternative to biomass-based fuels.[81] Such innovations have

[73] More information here: http://www.fao.org/mountain-partnership/our-work/focusareas/cleanenergy/ar/

[74] Ziv, G., Baran, E., Nam, S., Rodríguez-Iturbe, I., & Levin, S. A. (2012). Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin. *Proceedings of the National Academy of Sciences*, *109*(15), 5609-5614. Accessed: http://www.pnas.org/content/109/15/5609.full

[75] Otto, C. R., Roth, C. L., Carlson, B. L., & Smart, M. D. (2016). Land-use change reduces habitat suitability for supporting managed honey bee colonies in the Northern Great Plains. *Proceedings of the National Academy of Sciences*, *113*(37), 10430-10435. Accessed: http://www.pnas.org/content/113/37/10430.abstract

[76] Read more in the Economist's 2017 article on "A world turned upside down": https://www.economist.com/news/briefing/21717365-wind-and-solar-energy-are-disrupting-century-old-model-providing-electricity-what-will

[77] Researchers at Stanford have worked with Girl Scouts, utilities, Facebook, and other entities to study behavioral aspects of curbing energy waste: https://energy.stanford.edu/research/end-use-efficiency/energy-behavior

[78] More info about Portland-based gym using bikes to power their facility here: http://content.time.com/time/business/article/0,8599,2032281,00.html

[79] More info about harnessing electricity from our clothing here: https://www.nbcnews.com/mach/science/why-energy-harvesting-clothes-will-be-such-huge-deal-ncna797501

[80] Worland, J. (2017) "How batteries could revolutionize renewable energy." http://time.com/4756648/batteries-clean-energy-renewables/

[81] https://www.reuters.com/video/2017/08/07/human-waste-becomes-fuel-for-kenyas-urba?videoId=372265839

important implications in developing nations, which often lack the infrastructure needed for a centralized wastewater treatment plant.

Resilience

The term resilience has a wide range of definitions. In psychology, resilience refers to an individual's ability to manage, cope with, and adapt in response to adversity. In engineering, resilience is often used to refer to the ability to return to a previous state following a disturbance. And in ecology, resilience historically referred to the ability of an ecosystem to resist change (Holling, 1973).[82] However, in today's global society, facing global challenges such as climate change and social justice, a greater emphasis has been placed on understanding the interconnections between human and environmental systems. This emphasis on coupled socio-ecological systems (SES) has led to a new, but evolving, understanding of resilience as the ability of a system to: resist disruption, recover, adapt, and/or transform given an adverse event. While this broad definition of resilience generally aligns with the bulk of literature on coupled SES resilience, it should be noted that there are many different variations of this definition (see list of resources below for different definitions of resilience). Resilience in coupled SES is usually considered to be dependent on the biophysical setting, the context of the social system, and interactions between the two. A few examples of factors related to biophysical and social systems that may influence resilience are provided below.

<u>Biophysical</u>

- A system located in a low elevation, water rich physical setting may have a limited ability to resist disruption due to the potential for frequent flood events.

<u>Social</u>

- A system with a relatively large population of economically unstable residents may have a limited ability to recover and adapt as fewer financial resources will be available to support recovery following an adverse event.
- A system with a relatively large population of limited mobility residents may have a limited ability to resist disruption as residents may be physically unable to remove themselves from harm's way.

<u>Biophysical - Social Interactions</u>

- A system located in a resource poor physical setting may have a limited ability to recover or adapt following an adverse event such as a natural hazard.
- A system that is reliant on a single industrial sector (e.g., natural gas extraction) may have limited ability to recover and adapt following an adverse event affecting the industry.

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[82] Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual review of ecology and systematics*, *4*(1), 1-23. Accessed at http://www.annualreviews.org/doi/pdf/10.1146/annurev.es.04.110173.000245

Resilience Resources

- A brief overview of resilience: https://serc.carleton.edu/integrate/workshops/risk_resilience/what_is_rr.html
- Folke, C. (2006). Resilience: The emergence of a perspective for social–ecological systems analyses. *Global environmental change*, *16*(3), 253-267. Accessed at http://www.sciencedirect.com/science/article/pii/S0959378006000379
- Turner, B. L., Kasperson, R. E., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., ... & Polsky, C. (2003). A framework for vulnerability analysis in sustainability science. *Proceedings of the national academy of sciences*, *100*(14), 8074-8079. Accessed at http://www.pnas.org/content/100/14/8074.short
- Bocchini, P., Frangopol, D. M., Ummenhofer, T., & Zinke, T. (2013). Resilience and sustainability of civil infrastructure: Toward a unified approach. *Journal of Infrastructure Systems*, *20*(2), 04014004. Accessed at http://ascelibrary.org/doi/abs/10.1061/(ASCE)IS.1943-555X.0000177

Sustainability

Sustainability is the ability to meet the needs of the present generation, our own, in ways that also consider and provide for the needs of future generations. In essence, sustainable practices situate human needs while still maintaining social and ecological characteristics of places. [83] Sustainability is an important concept since it guides us to solutions that will work over a very long period of time and will allow future generations of human beings to inherit the resources to meet their food, energy, and other product needs and to live in a healthy environment. Sustainability as a policy finds it origins in the Brundtland Report of 1987.[84] It argues for creating a common future for communities to grow by incorporating global environment and development issues simultaneously.

Designing our future energy and products in a sustainable way

Designing in a sustainable way begins with the simple understanding that some resources are available in a limited supply, and some resources are available in a limited, but renewable supply. Non-renewable, limited resources include things such as the amount of land, water, oil, coal, natural gas, and minerals in our accessible resource pool. Renewable resources include things such as sunlight, wind, geothermal, and water-movement (hydro-based) energy. However, renewable resources are not available in a limitless supply over a short period of time, and are not always available "on demand". However, in discussing sustainability both renewable and non-renewable resources need to be considered to measure over all benefits to humans but still be contained within the specific c biophysical environment.[85]

Measuring Sustainability

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[83] Kates, R. W., Clark, W. C., Corell, R., Hall, J. M., Jaeger, C. C., Lowe, I., ... & Faucheux, S. (2001). Sustainability science. *Science*, 292(5517), 641-642.
[84] Brundtland, G. H. (1987). Our common future—Call for action. Environmental Conservation, 14(4), 291-294.
[85] Moldan, B., Janoušková, S., & Hák, T. (2012). How to understand and measure environmental sustainability: Indicators and targets. Ecological Indicators, 17, 4-13.

Designing an activity or reaching a goal in a sustainable way also begins with a consideration of human values that may be difficult to measure or quantify. In measuring the *sustainability* of an activity, there are three aspects to consider: 1) economic sustainability, 2) environmental sustainability, and 3) social sustainability. These three areas can be seen as overlapping, and an ideal sustainable activity will satisfy concerns raised in all three areas.

In summary:

1. The definition of "sustainability" for our class purposes is the ability to meet the needs of the present generation, in ways that also consider and provide for the needs of future generations.
2. Sustainability is important because it guides us to solutions that will work over a very long period of time.
3. In measuring *sustainability*, there are three aspects to consider: Social, Economic and Environmental criteria. A sustainable solution will address all three areas.
4. Technological advances, time scale and size scale all influence sustainability.

Sustainability Resources

- An overview of sustainability https://www.epa.gov/sustainability
- National Research Council. 2011. *Sustainability and the U.S. EPA*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13152.
- Kates, R. W., Clark, W. C., Corell, R., Hall, J. M., Jaeger, C. C., Lowe, I., ... & Faucheux, S. (2001). Sustainability science. *Science*, *292*(5517), 641-642.
- Kuhlman, T., & Farrington, J. (2010). What is sustainability?. *Sustainability*, *2*(11), 3436-3448.

B. Game Pieces

Chance Cards

DROUGHT

A large drought strikes your community. Lose one drinking water card per population card.

FLOOD

A large flood strikes your community. Lose one food card.

TORNADO

A large tornado strikes your community. Lose one electricity card.

RAINS

Your community experiences large rainfall. Pick up one drinking water card.

BUMPER CROP

Your community experiences a bumper crop. Pick up one food card.

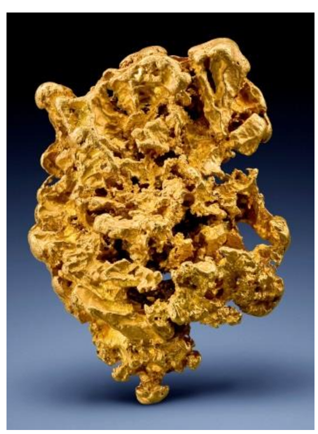
MINERAL LODE

Your community finds new mineral reserves. Pick up one electricity card.

MIGRATION

Members from a nearby community are displaced. Trade in all of your products for population cards.

GOLD RUSH

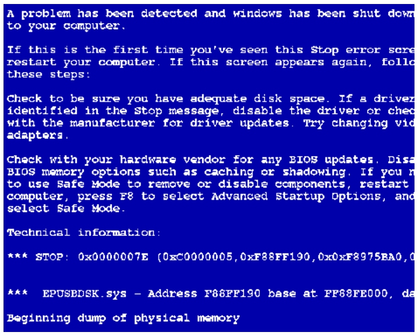


Your community strikes a gold vein. Pick up 5 tokens.

EPIDEMIC

Your community is stricken by an epidemic. Lose one population card.

TECHNICAL ERRORS



A technician makes an error and short circuits one of your facilities. Pay 1 token to get it back online.

Development Card

Road or **Facility** 1

Drinking Water

W 1

Food

W L 1

Electricity

W M 1

Development Card

Road or **Facility** 1

Drinking Water

W 1

Food

W L 1

Electricity

W M 1

Development Card

Road or **Facility** 1

Drinking Water

W 1

Food

W L 1

Electricity

W M 1

Development Card

Road or **Facility** 1

Drinking Water

W 1

Food

W L 1

Electricity

W M 1

Population Card

5 points

Population Card

5 points

Population Card

5 points

Population Card

5 points

Population Card

5 points

Population Card

5 points

Population Card

5 points

Population Card

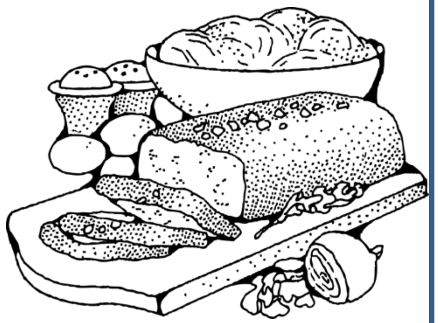
5 points

Population Card

5 points

Drinking Water

1 point



Food

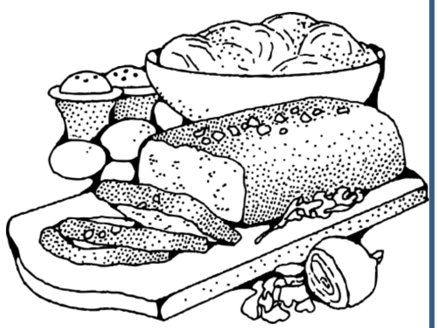
1 point

Electricity

1 point

Drinking Water

1 point



Food

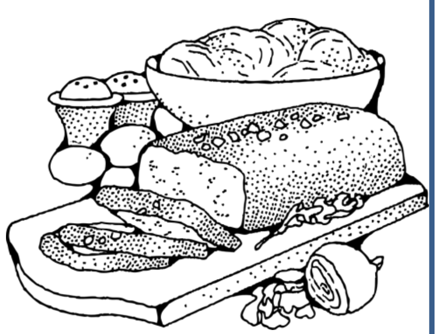
1 point

Electricity

1 point

Drinking Water

1 point



Food

1 point

Electricity

1 point