

Concept Paper

Defining the Nature of the Nexus: Specialization, Connectedness, Scarcity, and Scale in Food–Energy–Water Management

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Abstract: There is an increasing appreciation that food–energy–water (FEW) nexus problems are approaching criticality in both the developing and developed world. As researchers and managers attempt to address these complex resource management issues, the concept of the FEW nexus has generated a rapidly growing footprint in global sustainability discourse. However, this momentum in the FEW nexus space could be better guided if researchers could more clearly identify what is and is not a FEW problem. Without this conceptual clarity, it can be difficult to defend the position that FEW innovations will produce desired outcomes and avoid unintended consequences. Here we examine the growing FEW nexus scholarship to critically evaluate what features are necessary to define a FEW nexus. This analysis suggests that the FEW nexus differs from sector-focused natural resource or sustainability problems in both complexity and stakes. It also motivates two new foci for research: the identification of low-dimension indexes of FEW system status and approaches for identifying boundaries of specific FEW nexuses.

Keywords: food–energy–water nexus; sustainability; food security; water security; natural resource management

1. Introduction

As the world’s population approaches ten billion people by 2050 [1], food, energy, and water security have become important societal priorities. In response, various regulatory and research entities have recognized this challenge and are developing large-scale programs to investigate problems at the nexus of food, energy, and water, in what has been coined the “FEW” or “WEF” nexus (for FEW nexus [2,3], for WEF nexus [4,5]; while distinctions between the WEF and FEW nexus concepts may exist, currently evidence for this is lacking and here we treat the terms as synonymous). Numerous workshops and symposia have also been convened, at least partially motivated by the recognition of differential trajectories of supply and demand for food, energy, and water resources in the developed and developing world (e.g., Rio+20, [6]). Subsequently, governments of both the United States [7] and European countries [8] have funded millions of dollars for FEW nexus research since 2016. As the FEW

nexus rapidly becomes an area of research importance globally, a transparent strategy for addressing the emerging externalities and increasing complexity of the integrated FEW nexus is clearly needed [3,9].

In spite of the current momentum, a conceptually clear definition of a “FEW nexus” remains elusive [10–12]. Descriptions of the FEW nexus are numerous, with many being aspirational rather than definitional, describing desired outcomes from the perspective of a well-functioning FEW nexus (e.g., [13,14]), rather than the structural features of the nexus in a manner that empowers anticipation of emerging FEW problems. Currently, structural definitions of the FEW nexus commonly refer to the three sectors, with an increasing call for focus on the connections among these sectors (e.g., [5,15]). However, such descriptions risk being both too trivial and too ambitious. The trivial risk is that any study of individual sectors likely already acknowledges there are connections with other sectors (e.g., input and output of goods and services), even if these connections are not explicitly represented or modeled [16]. The risk is that exact connections between the three sectors may be only partially recognized. In fact, the connections between the FEW sectors may be indefinitely numerous, each with different relative strengths and with magnitudes which are often unknowable *a priori*. Nor is it clear that all potential points of contact are subject to control within existing regulatory or institutional structures, questioning the salience of attempts to comprehensively inventory the connections between sectors [17]. Consequently, a complete representation of a FEW nexus based on this definition is likely to be of limited utility even if it could be fully modeled [18]. Indeed, the distinction between sectors and boundaries itself has been critiqued as artificial, potentially obscuring important dynamics within and across sectors [19].

In the absence a clear definition, it is difficult to determine whether the FEW nexus that is now receiving so much attention merely differs in scale from other types of resource management involving food, energy, and water, or if it differs in kind. For instance, if the FEW nexus as a concept is simply repackaging an existing theory, we miss important opportunities to build on previous scholarship (e.g., [10]). At the most granular level, all living things individually manage food–energy–water problems to survive (e.g., optimal foraging theory [20]). Yet, treating the food–energy–water management of individual organisms as a “FEW nexus” would be an artificial and unhelpful abstraction of what is recognized already as the natural history of an organism. At the most inclusive level, globalization has telecoupled resource consumption and production into a highly complex, multi-agent, multi-resource set of feedbacks [21] that link people and resources into an “Earth-system” network [22–24]. Capturing this complexity would require a FEW concept to be a “concept of everything” with little utility left to address specific, operational FEW problems.

A tractable and rational definition of a FEW nexus would lie between those two extremes. A minimally adequate definition of a FEW system must meet the conditions of (1) salience, (2) selectivity, (3) universality, and (4) scalability (see Text Appendix A). The condition of salience, or sensitivity, requires that any definition of a FEW system must correctly identify food–energy–water production and/or management, or what a FEW nexus is. Selectivity, in contrast, discriminates what is not a FEW nexus. Further, any useful definition requires the flexibility or versatility to recognize interactions among a diversity of food, energy, and water production systems, and the universality to capture the key conceptual elements of any nexus regardless of geographic or technical context. Finally, although there is likely a global FEW nexus, for research and informed management to be tractable we need to be able to recognize FEW nexuses on a variety of scales in a framework where observations can be applied to testable hypotheses [17]. A researcher may assert that a specific case is a FEW nexus, but if their focal system does not satisfy all these conditions, their otherwise useful research may not inform the conceptual understanding of other FEW nexuses.

Until we have developed a clear conceptual identity for the FEW nexus, it will be difficult to defend that this topic represents a unique research problem, or assert with confidence that functional solutions to FEW problems have been identified to date. In this paper, we start with a short review of the FEW system origins of what is now widely recognized geopolitical crisis to provide a recognizable exemplar of one FEW crisis, and how challenging such an example can become (Section 2). Then, we review the ontology of FEW systems to inform the scope of a FEW system definition (Section 3). We

then propose a set of characteristics, that when all present, serve to distinguish a FEW system from a non-FEW system (Section 4). We then use these characteristics to identify under what conditions “FEW crises” develop (Section 5), and lastly discuss some two emerging possibilities for possible research foci for quantitative FEW research (Section 6).

2. The FEW Crisis in Yemen

A critical look at the origins of a current geopolitical crisis may help identify distinct FEW insecurities at their roots. As of this writing, the situation in Yemen presents a relevant case study, demonstrating the synergy of multiple simultaneous stressors working together and the distinctiveness of FEW problems. Certainly, not all aspects of the Yemen case will present in every FEW system problem, but it does illustrate real-world manifestations of the conceptual FEW components. Historically, Yemen has been both an archetypal desert nation and a regional agricultural power. Nested in a particularly arid region, Yemen is one of the 10 most water-scarce countries in the world [25], yet has a long history of agricultural success. The city of Mocha for example, has been a center of coffee production and trade since the 15th century [26,27], with the name itself becoming iconic for the beverage.

Most recently, a series of stressors have worked synergistically to drive Yemen to its current state of crisis and civil war [28]. In particular, agriculture in Yemen transitioned from a historical diversity of consumable produce and cereals to a greater reliance on a dominant cash crop, Qat or Khat (Figure 1). Qat is a stimulant and has a long history of religious and recreational use in the Red Sea region—the sale of which in good years could be used to offset loss of food production. Qat cultivation has increased from approximately 10,000 hectares in the 1970s to 168,000 hectares in 2012—roughly 16-fold [29]. It is also a crop with a relatively high demand for water. It has been estimated that Qat consumes 37% of Yemen’s irrigation water use [25].



Figure 1. Qat fields in western Yemen. Photo: CC BY-SA 3.0 Antti Salonen.

The shift from predominately food crops to Qat was facilitated by low energy prices and the lack of regulation, which in turn propelled a substantial increase in well drilling to pump groundwater for irrigation. The continuing low cost of energy has allowed farmers to tap groundwater resources to

support 40% of the ten-fold increase in irrigated agriculture in Yemen between 1970 and 2004 [25] which correlates with a drop in aquifer reserves. Pumping has so outstripped recharge that groundwater levels have been estimated to be falling 2 to 6 m per year, with recent wells descending over 1200 m in depth to reach the retreating aquifer [30]. Thus, low-cost energy has provided low-cost irrigation water to an otherwise arid landscape, lowering the cost of production of a water-intensive crop, and increasing the value of the water used in Qat irrigation. Predictably, farmers have put their land to the highest valued use—cultivation of Qat—with a correlated loss of food production, lowered aquifer levels, and reduction in food security.

Superimposed on this same stressed food security landscape are several synergistic external challenges. First, Yemen's population growth has been one of the highest in the world, growing at an average of 3% per annum since 1960 [31]. At the same time, increasing temperatures and decreasing precipitation associated with climate change have challenged the ecosystem and regional water security [32–34]. In addition, political instability has increased as existing institutions that have been seen as ineffectual and corrupt by residents are unsupported [35,36]. Concurrently, Yemen has faced a wave of regional political challenges from Morocco to Afghanistan, which have catalyzed polarizing and sometimes violent changes, exacerbated by investments from military powers conducting a struggle for regional power by proxy [37–39].

At this point in time, it is not possible to attribute the current crisis in Yemen to any single one of these stressors. Clearly however, Yemen was in a state of FEW stress when the combined impacts of population growth, regional power struggles, and climate change were applied simultaneously. Retrospectively, one can see how connections among the three sectors have contributed to a system-level response; changes in the energy sector are transacted through the water sector to the food sector with a net system-level loss of security. To learn from such examples, and to identify others that are emerging, a clear definition of what is and is not a “FEW nexus” is needed, as well as when these systems transition to crisis. With this paper, we seek to develop such a conceptual foundation that provides greater specificity as well as more achievable and manageable research targets [18,40,41]. Identifying the salient features of the FEW nexus will depend on correctly framing FEW problems and in turn the research agenda [42].

3. Development of the FEW Nexus

If individual and organismal foraging and the current crisis in Yemen form clear archetype end-points on a scale from a non-FEW nexus to a FEW nexus crisis respectively, where on that scale are the transitions to a bona fide FEW nexus, and then to a FEW nexus crisis? The historical ontogeny of FEW systems, and specifically the transitions from proto-FEW systems to contemporary FEW systems and where problems have arisen, initially inform our perspective on the definitive elements of the FEW nexus.

Historically, the FEW nexus was necessarily managed at a much smaller scale, making it easier to see how changes in the availability or quality of one resource affected the others. For example, subsequent to the transition from nomadic hunter–gatherer to sedentary agriculturalist and prior to the 1900s, the number of livestock managed by a farmer typically depended on their ability to procure consistent feed for these animals from nearby, accessible, land and water resources. Balancing livestock production depended on a farmer observing and reacting to changes in available food, energy, and water resources. The transparency at this local scale imposed a set of checks-and-balances that, while perhaps not optimally efficient, was an effective mechanism for ensuring relative sustainability (Figure 2a).

Major historical milestones, such as the rise and fall of empires and the emergence of new technologies, have led to responses in both the geographic scope and degree of specialization in food, energy, and water systems across societies over time. The establishment of the Roman Empire allowed for the substantial trade of essential grains across the Mediterranean Sea and complex water transportation infrastructure [43–45]. European imperialism led to the extensive extraction of Peruvian guano for use as a fertilizer to increase food production in Europe [46]. More recently, the Industrial Revolution brought myriad changes in the management of food, energy, and water systems [47]. For

example, the discovery of the Haber–Bosch process made it possible for fertilizer to be generated off-site by specialists, and led to a 30%–50% increase in crop yields globally [48,49]. FEW specializations continue to emerge (e.g., water use efficiency innovations, dynamic water rights, GMO crops).

Yet, complex supply chains over a larger geography conducted by individuals with more specialized knowledge will, on average, result in further distinction among sectors (Figure 2b). For example, in the Columbia River Basin in the Pacific Northwest, in the United States, users who depend on water stored in surface reservoirs now face regular curtailments, as there are ever-growing needs for hydropower production and agriculture while meeting instream flow requirements for endangered salmon [50–52]. These competing water demands in the food, energy, and (water-dependent) wildlife conservation sectors create significant frictions and calls for increased innovation to address FEW problems. Development of independent sector identities and the propagation of sector-specific innovations are increasingly appreciated at a system or multi-sector level of complexity.

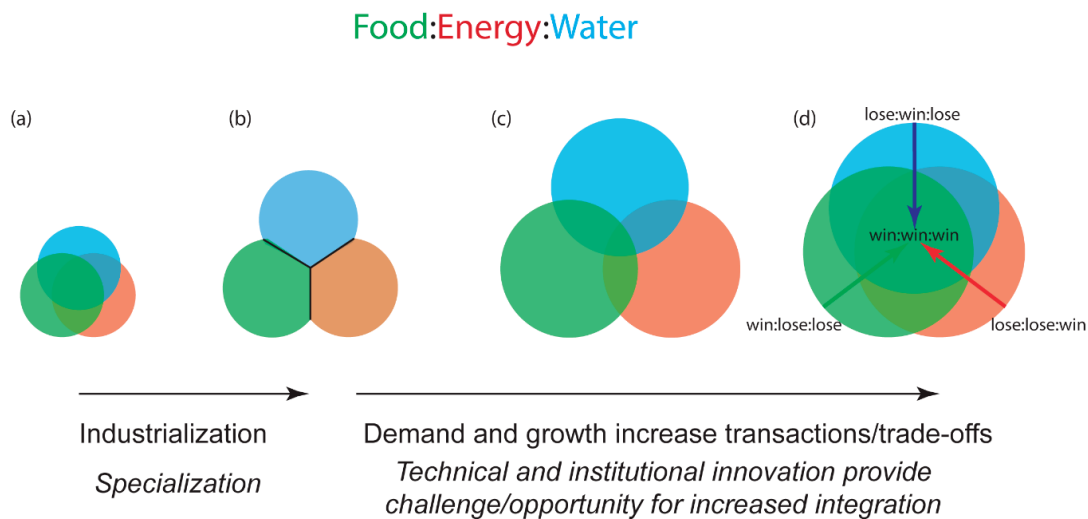


Figure 2. Evolution of the food–energy–water nexus (FEW). (a) Individuals acting as integrated FEW systems making resource acquisition decisions, where costs, benefits, and trade-offs are evaluated on immediate scales with relative integration. (b) As the FEW system evolves, specialization within sectors increases, with some degree of transaction of resources across boundaries. This is anticipated to correlate with increases in production efficiencies, but at the potential cost of integration. (c) As system level complexities increase in the face of increased demand, but with limited resources, the emergence of system-level dynamics results in functional interdependencies—illustrated here with increasing overlap. These overlaps or trade-offs are potential areas of friction in the absence of technical and/or institutional innovations that leverage potential, system-level synergies. (d) In the face of global limits to resource availability (total colored area = total resource availability) and increasing demand for food, energy, and water resources (the size of each circle), sustainable solutions will require leverage of potential synergies in the overlapping areas.

4. Defining Characteristics of a FEW Nexus

In this paper, we advance the case that FEW nexuses have three characteristics that present challenges beyond those that face other resource management sectors: (1) specialization within sectors that supply survival-supporting goods and services, (2) connectedness and associated inter-dependencies across boundaries that separate sectors, and (3) the potential for scarcity or other constraints on FEW resource availabilities that translate across sector boundaries. It is likely that these features alone will not surprise readers. However, we argue that resource management systems that do not capture all of these three characteristics cannot properly be called FEW nexuses, and conversely, proposed solutions that do not address all three components are unlikely to resolve bona fide FEW nexus problems. With a

description of the FEW nexus in hand, we will show how FEW nexus problems, or crises, can emerge only as a system-level state, rather than arising in one sole component of the nexus.

4.1. Specialized Sectors

Specialization in any sector is the outcome of increases in production efficiency and optimization, and has been an important part of resource management since at least as far back as the 18th century with Smith's *Wealth of Nations* [53]. Skilled individuals can produce a given resource in greater quantities, at a faster rate, for a lower cost, if they are specialized and dedicated to its production. As long as the output from one sector is effectively connected to the input of the other sectors, the FEW enterprise can leverage these increases in efficiencies at a system-wide level. As more workers specialize in the production of one of the sectors, management of those producers likewise becomes specialized. The silo-ing of sectors is already widely acknowledged in the FEW nexus literature (e.g., [14,54]), but if it is an inevitable step in the evolution of the means of production, then our definitions of the FEW nexus concept must be similarly explicit with respect to specialization of sectors.

The development of FEW sectors has made it possible to manage and distribute resources beyond the local scale [24]. Doing so has also allowed the management of FEW sectors to become increasingly disconnected from each other and without explicit management feedbacks from the other sectors, but with some indirect feedbacks via economic forcing (e.g., [10,14]). Indeed, the sectors themselves are often perceived to be agents in competition, rather than components of a common FEW system. For example, water in large, dammed rivers is often used for both food and energy production, but because of complex and largely independent institutions, the water and energy sectors are seen as competitors for available instream flow rather than parts of a synthetic FEW production enterprise [10,55]. This fundamental competition between sectors is seen in river systems around the globe (e.g., [56]). The recognition that FEW sectors are specialized is key to distinguishing modern FEW problems from the simpler survival problems of individuals. However, specialization in production is not sufficient to define a FEW nexus (see text Appendix A), and specialization does not by itself cause a FEW crisis.

4.2. Cross-Boundary FEW Transactions

While the production and management of FEW resources is typically specialized, production methods and management policies are often both directly and indirectly connected across sectors. In the Columbia River Basin, for example, surface water and groundwater are both used for agriculture, but hydropower is driven almost exclusively by surface water, and groundwater pumping is energy intensive. Historically, research on the role of groundwater in agricultural drought tolerance has proceeded independently of research on how surface water is used and/or impacted during droughts (e.g., [57–59]). Viewing the transactions from a FEW system perspective, it becomes more apparent that groundwater substitution for irrigation negatively affects hydropower productivity when both surface water supplies are low and energy needs are high during summer periods [60]. Thus, management decisions in one sector of an integrated FEW system will have implications for the other sectors. Similar examples of critical, boundary-related complexity exist at many of the FEW boundaries (Table 1, and see [24,61]).

It is tempting to focus on sectoral boundaries and transaction costs as key points of friction in, or definitional of, the FEW system (e.g., [15,62,63]). However, while a focus on sectoral boundaries is necessary, it is insufficient for, and can hinder an integrated understanding of FEW dynamics important for those using and managing FEW resources. For example, scale-mismatch of economies and institutions within different FEW sectors can be obscured by focusing strictly on the transaction across one or more of the FEW boundaries. In addition, the FEW goods and services provided within each sector may have different capacities for storage, and thus different capacity to absorb shocks or ephemeral shortages without affecting system-level dynamics—a capacity not revealed in a framework focused exclusively on transactions at boundaries. Thus, productive models of FEW systems must achieve a balance between a focus on the sectors themselves and the boundaries between them; it seems likely that research models of diverse FEW systems will require unique balances in this respect [19].

Table 1. Examples of complex transactions at FEW sector boundaries that may manifest the complex dependencies, either positive or negative, across FEW sectors. These examples may not manifest at every FEW sector boundary, but do illustrate the potential degree of complexity. Photos: Algal bloom, CC-BY-3.0 Felix Andrews; Internationally sourced tomatoes, Stephen Katz; Groundwater pumping, CC-BY-SA-3.0 John Poyser; McNary Dam on the Columbia River USA, public domain from US Department of Energy; Combine harvesters, Ryan Archer from Pexels; Composting vegetables, open source by Ben Kerckx.

Water–Food	Growing access to irrigation increasing global fertilizer and associated nutrient runoff (water pollution)	
Food–Water	Reduction of water vulnerability via water embedded in imported food (i.e., virtual water)	
Water–Energy	Groundwater pumping for irrigation reducing streamflows for hydropower production	
Energy–Water	Water storage for hydropower that otherwise supports agriculture and wildlife	
Energy–Food	Wide-spread use of mechanized farm equipment to support large-scale agriculture	
Food–Energy	Composting food waste for energy production	

Beyond the production of FEW resources themselves, management also currently exists in disconnected silos, creating gaps in knowledge that hinder an integrated understanding of the science, technology, and governance of FEW systems. For instance, in the water sector alone there are over 30 federal agencies, boards, and commissions in the United States with water-related mandates, all of which approach water management with varying interpretations of what constitutes a water resources system and different perspectives on desired water supply, demand, quality, and quantity objectives [64]. Similar disconnects within the food and energy sectors complicate the integration of knowledge within and between sectors, which can lead to inaccurate and imprecise science and modeling outcomes, counter-productive technological developments, and ineffective policies. For example, in multi-sector governance where individual sectors exert regulatory leverage out of proportion to the associated resource production and flows, a focus on resource flows can be misleading [19]. In the Columbia River Basin specifically, regulatory frameworks governing recovery of endangered salmon often determine water availability for agriculture and hydropower generation in spite of the modest size of the salmon fishery. Resolving FEW system models that integrate both a balance of within-sector and transboundary dynamics, and also the balance of management mechanisms and governance structures, is daunting [62]. This problem may yet require the development of a new vocabulary, conceptual framework, and set of metrics to describe, assess, and compare these systems.

4.3. Potential for Transactions that Propagate Scarcity throughout the System

As long as FEW resources are consistently available and relatively inexpensive or easily substitutable (e.g., energy from coal vs. hydropower), FEW transactions proceed as low-friction commerce. Were this a single sector model, this characterization of scarcity impacts would be as simple as it sounds; as the perceived availability of a resource decreases, the marginal cost of the resource should increase with respect to both the current and potential future scarcity [65]. In some cases, the costs can increase more rapidly than the system can respond, and be perceived as a crisis. Critically, scarcity and crisis are based on perceptions and are conditioned on a wide range of socio-psychological and institutional factors (e.g., [66]), and thus are not absolute. Here we are addressing scarcity as it manifests in the behavioral responses of consumers in general, but we recognize that the triggers of specific behaviors may be case-specific. Regardless, those behavioral responses to perceived resource scarcity, resulting from either misallocation or environmental forcing, is perhaps the most easily identifiable characteristic of a FEW crisis.

In FEW systems, once a given key resource becomes scarce, expensive, or difficult to obtain (e.g., global oil shortages in the 1970s, the Saltpeter War for Peruvian nitrate in the 1880s, non-adaptive water rights in the Western United States), these scarcities can themselves be transacted across sectors, creating system-level problems. In Yemen, the FEW crisis has been associated with water scarcity. For a long time, groundwater extraction in Yemen was inexpensive due to low energy costs, and therefore intensive exploitation was supported, but with no management framework in place to sustainably regulate use. Ultimately, scarcity in one sector (water) caused by abundance (i.e., lack of scarcity) in another sector (energy) has been transacted across the sectoral boundary into a third sector (food). Once the water use began affecting food security, the whole FEW system moved toward critical instability. Perturbed by outside forcing (drought, institutional challenges), the specified FEW system was then able to transition to FEW crisis. Implicit in the idea that scarcity transacts across boundaries is that the sectors involved produce essential goods (see Text Appendix B).

In some cases, scarcity in a given sector has been avoided by disconnecting resource consumption from production at the local scale. The city of Los Angeles is a classic example, having secured much of its municipal water from watersheds hundreds of kilometers away during the first half of the 20th century. These large water imports allowed the urban population and economy to grow rapidly, but decimated those distant source watersheds that were drained to support Los Angeles' demands [67]. This ability to disconnect resource management and place to avoid scarcity has made it easier to acquire, transport, and use FEW goods from distant sources, but much harder to know whether sources of these goods are managed sustainably [22,68]. Indeed, this disconnect permits populations to increase

beyond local environments' provisioning capacity, which is intrinsically brittle in the face of shocks such as interruption of international trade [69–71].

While it is facile to suggest that resource scarcity drives conflict, the reality is somewhat nuanced, and if present, the connections are often indirect [72]. Empirically, water scarcity has been implicated as the catalyst in only a small number of regional conflicts [73]. In retrospect, technological change, innovation, and the importation of capital from outside the system under study generally allows those systems to escape a scarcity-based conflict [72]. Still, responses to FEW system problems often amount to calls for increases in allocative efficiencies or technological change that in effect remove scarcity via a shift in the demand curve (*sensu* [65]), or what is effectively a redefinition of scarcity (e.g., [54]). This aspect of innovation calls into question the initial characterization of scarcity, and reinforces the need for conceptual clarity for which we are advocating.

4.4. *Crisis within a FEW Nexus vs. a FEW Nexus in Crisis*

As mentioned above, a defining feature of FEW nexuses is that they have the potential to propagate scarcity found in one sector throughout the entire FEW system. When that potential is realized it is possible to say that the FEW nexus is in crisis, which has in part motivated the nexus approach. Indeed, definitional of these nexuses is the apparently paradoxical combination of the specialized sectors with independent development histories that are at the same time transacting and dependent on one another. It is when managers or producers in one sector take actions to deal with their immediate scarcity, which in turn affects scarcity in the other, interconnected sectors, that system-level crises result. It is a principal intent of the nexus approach to identify adaptations and innovations that prevent problems from propagating from sector to sector across the entire system.

Not every problem in a FEW nexus must lead to a FEW nexus in crisis. If scarcity in one sector can be isolated from the rest of the nexus, it may be possible to resolve that crisis before it propagates across the entire FEW system. It has been suggested that resource storage, or reserves, may provide a buffer for systems to avoid the transition from a within-sector problem to a nexus-wide crisis (e.g., [24,74]). For example, water storage in reservoirs in wet seasons can provide irrigation supply later in time during drier seasons, preventing water scarcity in that time of year when it might otherwise impact hydropower production capacity. It remains to be seen if there are limits to this utility imposed by mismatched capacities for storage that exist within the FEW sectors; water can remain in reservoirs for long periods, but food spoils rapidly, and there is little to no storage capacity within electrical grids. Indeed, the nexus concept itself has been critiqued as hiding certain resource issues and constraints by aggregating diverse activities within sectors of a nexus [19]. If the nexus approach is to bear fruit, identifying ways to insulate sectors while maintaining transactions among them will be a critical research need.

5. How Do these Criteria Perform?

We have mentioned that FEW crises are distinct in terms of three necessary characteristics: specialization, transactions, and the propagation of scarcity. Do these criteria present an adequate set of conditions to sensitively and selectively define a FEW nexus? (see text Appendix A). In the absence of such a set of previously identified exemplars of “FEW” and “non-FEW” to which our criteria may be applied, here we outline four archetypes representing these combinations, and ask how the proposed criteria perform. The cases are summarized in the conceptual map in Figure 3.

Two of these examples are cases that have been mentioned above. We asserted earlier that an individual organism manages food–energy–water problems for survival, but that this idea is already captured conceptually by the natural history of that organism. Indeed, within a single individual we do not see specialized sectors with boundaries. In this way, the foraging individual represents a case of a “non-FEW system”. In contrast, we also detailed the case for Yemen as an example of a FEW system in crisis. FEW provisioning in Yemen is highly specialized and FEW resources are liberally transacted across sector boundaries. The potential for scarcity to propagate throughout the system is realized by the fact that water scarcity led to a collapse of food security.

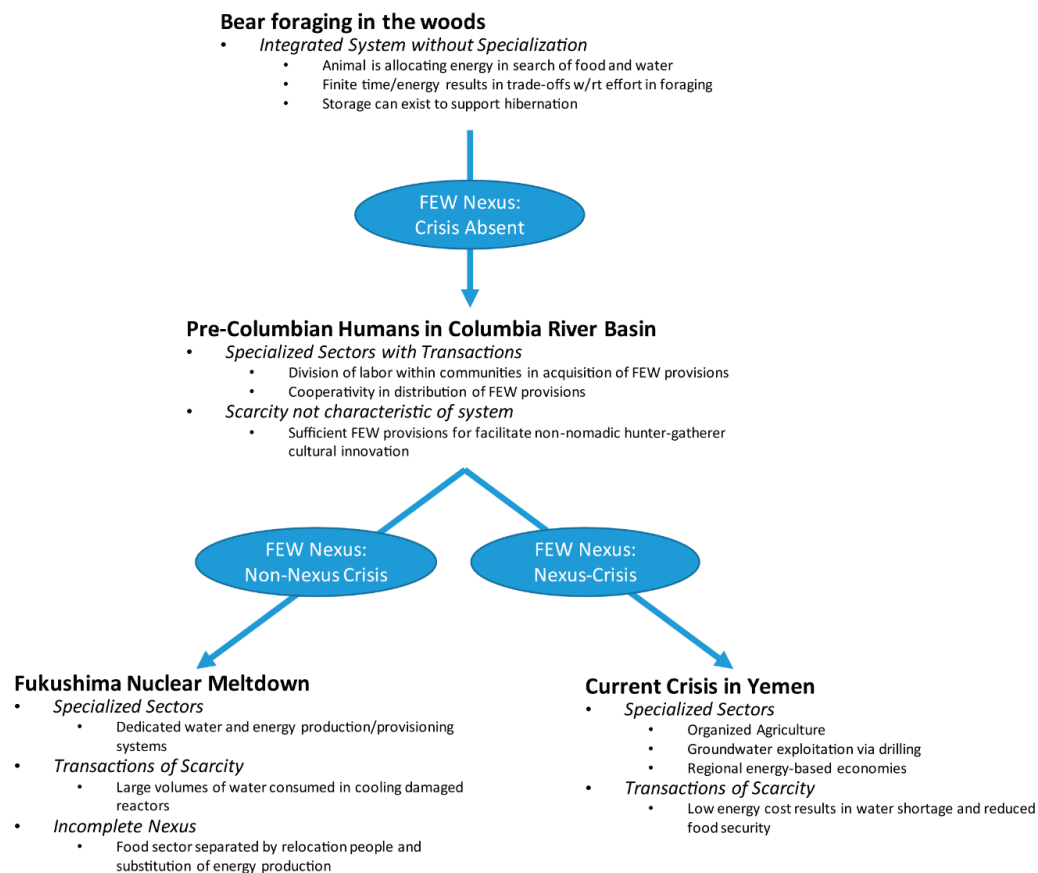


Figure 3. Conceptual relationships between systems discriminate FEW/non-FEW and problem/non-problem cases. Not all situations related to food, energy, and water are a FEW nexus or in need of a FEW nexus solution; this relational map illustrates how the criteria within the definition of a FEW nexus can discriminate cases. The arrows in this figure are intended to indicate conceptual transition, not necessarily temporal or developmental flow.

To explore the other two possibilities, we introduce two additional archetypes: the Fukushima-Daiichi nuclear power plant meltdown following the Tōhoku earthquake in 2011 (a non-FEW system problem), and Pre-Columbian humans in the Columbia River Basin (a FEW system not in crisis). Under normal operations, nuclear power is one of the most water-intensive forms of energy production, with mean obligations of 200–800 gallons of water per MWhr [75]. The Tōhoku earthquake resulted in a seismic ocean wave that flooded the Fukushima-Daiichi nuclear reactor, causing a loss of power to the reactor’s cooling systems and an eventual meltdown in the reactor core [76]. In response, authorities maintained a system for pouring cooling water, diverted from other water uses, into the reactor containment building in an effort to prevent explosions within the core of the damaged power plant [76,77]. In the Fukushima case there was distinct specialization within the water and energy production sectors, with clear transactions as vast quantities of water were poured into the damaged reactor, contaminating the water and making it unavailable for any other use. Indeed, at the time there were forecasts that there would be insufficient water to prevent an explosion within the damaged reactor core [76,78]. Transactions across the water and energy sectors, and the relationship between scarcity and problem, are here recognizable. How these large radioactive discharges could impact the food sector in the long run is less clear; especially since the principal criticality in this example seems to be based on the lethality of radioactive emissions [79,80]. However, even if the radiation release resulted in decreased food security, the lost security is not due to extending and intensifying scarcity via a transaction as much as via a complete loss of access. In fact, steps such as mass evacuations were

taken at Fukushima-Daiichi to isolate the impacts of the meltdown from the FEW system to which it otherwise used to be a part. Thus, this case represents a problem (a profoundly costly one) within a FEW system, but not a system-level FEW nexus in crisis.

Among the Pre-Columbian indigenous people in the Columbia River Basin, we see a hunter-gatherer culture with a division of labor among specialists in fishing, gathering wood, and other domestic tasks [81,82], and the production of each sector shared (transacted) within and between tribal groups [81,83]. However, resources were predictably sufficient in this region that these groups adopted a non-nomadic lifestyle. This level of food, water, and energy security was distinctive, and the abandonment of nomadism among hunter-gatherer peoples it empowered was similarly unusual. Thus, it was a FEW system by criteria, but the lack of realized scarcity or shortage makes it non-problematic.

6. Deploying this FEW Nexus Definition

We propose that two areas are high priority topics for research exploration: the development of low-dimension measures of FEW system states, and means of identifying the boundaries of the FEW problem, or “FEWshed”. Progress on these topics will increase the potential for comparative studies, and to generalize solutions across systems.

6.1. Characterizing FEW Capital

Central to the FEW nexus concept is that the same stocks of resources can be used for multiple purposes, and using some for one leaves less to be used for another [10]. This suggests tradeoffs among resource allocation and production outcomes (e.g., production possibilities frontiers in economics, [84]), where the management choices of specific tradeoffs are realizations of relative values. Such values could be set ahead of time by a single centralized planner, or a small group of elected or appointed citizens, or emerge post hoc from choices made without explicit regard to priorities; in any case, the political context affects the setting of values. Regardless of the context, a current challenge to evaluating these tradeoffs and their consequences is the development of a system-level indicator that expresses FEW system status.

Expressing system status in terms of a fiat currency like dollars or Euros is common, but in no way fundamental. In environmental economics modelling, it is standard practice to label some variables with “prices” where there is a reference, or with numeraire, the price set for mathematical convenience to 1, with the values for all of the other goods quantified relative to that reference. The units for the value system can be joules, bushels of wheat, number of fish, hours of recreation, acre-feet of water, or any commodity intrinsic to the system under study. This is convenient, and therefore commonly done, in providing a common unit of price to characterize diverse values, and in so doing facilitate the application of models to observational studies. However, even if one proposed to express value in terms of a resource intrinsic to the system (e.g., units of water [85–87]) rather than an extrinsic currency, focusing on one particular resource as a currency places the focus on that resource rather than on the interconnected system [10].

There are two additional factors that make food, energy, and water, and the nexus between them, different in a way that justifies a new indicator of system status. First, values derived from observed decisions at the level of individuals will be highly problematic because the full implications of the decision are not borne by the decision maker. For example, there are common instances where an agreed upon or “fiat” currency will not capture the full value of a resource for some stakeholders (e.g., the price of extinction of endangered species or the social capital expended in negotiations). Second, there is typically a substantial degree of regulatory and managerial specialization which prevents or obscures the consideration of interactions and tradeoffs between sectors. For example, the Columbia River Treaty dictates priorities for dam operations over flood control, hydropower, fish habitat, and irrigation. The durability of the agreement however, and the extent to which it is adhered to, are subject to scarcity in resources outside of flood control services [88]. Thus, the fiat currency, which may adequately specify the values being traded in the production process, is an incomplete specification of the values being traded in the regulatory or decision making process.

As a result, describing a FEW system state becomes a problem of specifying (1) the characteristics of outcomes, (2) the denomination of values over alternatives, and (3) the system by which one outcome among many is chosen. As was discussed, we may prefer one value over another either in terms of one of the goods or a fiat currency, but something is lost in relying on a reference value that requires a methodological innovation, including information lost about the state of one resource when it is valued in the units of another [89], and psychological factors that cause values to be affected by the system of denomination [90]. We are left still looking for an indicator of FEW system status that can capture the performance of trade-offs among FEW sector resources and the effectiveness of FEW system management. Significantly, while the FEW nexus is currently three-dimensional, the need may arise in future to evaluate other finite resources such as soils in a higher dimensional nexus; the development of state variables for the nexus would benefit from being inclusive and flexible in this regard.

Recently it has been suggested that performance targets, such as the Sustainable Development Goals (SDGs), could be useful measures of FEW system performance [14,91]. The argument that SDGs can retrospectively indicate success in meeting aspirational goals for deliverables within sectors of a well-functioning FEW nexuses is persuasive [92], and for managers who are principally concerned with meeting performance targets, they likely have high value. However, in evaluating potential or emerging FEW problems in real time it is not clear that performance targets are as useful as timely metrics of production, storage, access, and delivery within the sectors comprising the nexus [92]. For example, it is possible to conceive of multiple trajectories that a FEW system may take to arrive at a single performance target, not all of which the SDGs would diagnose; in any case these may not be equally desirable or even tolerable. Lastly, SDGs in particular are highly interconnected [93], and it is not clear how multivariate measures with numerous direct and indirect interactions will express a system-level index of state for the entire nexus. Indeed, this heterogeneity of response is an additional strong argument against a sector-specific currency, such as water.

As an alternative, we propose the development of a system-wide indicator of FEW system status that we might call “FEW capital”. Just as the formal finance sector tends to allocate financial capital towards its highest valued uses, anticipating that it maximizes societal well-being in aggregate (aka economic efficiency), FEW capital could represent the efficient allocation of resources across all sectors. Across a large, multi-use watershed, it is possible that one could operate hydropower projects at maximum capacity at the expense of irrigated agriculture and endangered species extinction risk, but still maximize net revenue generated from hydroelectric dams. Such a maximized revenue combined with profound imbalance in other sector resources is unlikely to maximize net societal well-being and, given sectoral interdependence, will decrease sustainability. However, if targeted research can resolve mapping balance in values across FEW resources onto societal well-being, such a measure of FEW capital will then be at hand to monitor and evaluate the success of policy and management decisions. In addition, there is no reason to expect such an integrating measure to be limited to three dimensions.

6.2. *The FEWshed—Managing Issues of Scale in Space and Time*

Recent research has increasingly highlighted the global scale of food, energy, and water production systems [24,94–96]. The globalization of the FEW nexus concept has been driven by recognition of the importance of global trade in FEW supply chains, and the ability to leverage regions of high production capacity in areas with production–demand deficits [21,22,24,95]. Innovative, globally-focused research has also revealed a rich dynamism not evident at local or regional scales [41], including the interactions between trade and surplus in determining system stability (e.g., [69,74]), and the apparently paradoxical decreases in food nutritional quality and public health arising from an increase in global food production [97,98].

Our ability to model a global FEW nexus notwithstanding, scarcity and crisis in the FEW system are perceived heterogeneously across the global FEW landscape. The Yemen case above is one example, but local to regional FEW systems are approaching criticality elsewhere, such as in northern India and central California [99–101]. Given the heterogeneity in regulatory and governance across the

global landscape, identifying a single solution to a FEW crisis, or even similar aspects of FEW crises, seems an unreasonable expectation. Indeed, some FEW solutions and innovations have characteristic scales (e.g., tradeable water rights) that limit the specific FEW problems that they can address. These different scales impose different capacities for innovation or growth that may or may not depend on the others in the short term. To make the FEW nexus operational therefore, and avoid a low-utility “theory of everything”, we are still left in need of a definition of characteristic scales to define a given FEW nexus—aka “the problem-shed” (sensu [17,102]).

Defining the characteristic scale of a FEW nexus, or “FEWshed”, is made still more difficult because FEW problems may be perceived by FEW consumers at specific scales, but the underlying dynamics within each FEW sector may have different scale dependencies. Some of these operational mismatches can be traced to historic constraints, as policy priorities within each sector have emerged in response to needs at different scales—e.g., regional famines driving food security, global geopolitics driving energy security, and water security managed within more local hydrologic units [14]. It is seductive to look to the water footprint, which emerges from accounting for FEW resources in terms of “virtual water”, or the direct and indirect water requirements of production, processing, and delivery [71,103], as a model for the FEWshed (e.g., [24,104]). Water footprints, or other analogous footprints, are particularly useful in accounting for total resource use in the production of FEW goods when those resources have been displaced by regional and global trade of the FEW goods (e.g., [71,104,105]). Water footprints however, have been problematic in this role for a number of reasons including scale mismatch among the FEW sector resources [24], lack of specificity with respect to what is or is not accounted for [41,106], and incompleteness [104]. Moreover, the focus on one FEW sector as a conceptual model of the system, similar to focus on one commodity as a currency, risks obscuring system-level features and dynamics that are not sector specific, as outlined above.

This inherent inability to align the global FEW nexus and specific FEW crises meaningfully across a useful scale is potentially a major problem for managers within the FEW systems. This suggests it may be impossible to define a “FEWshed” in the same way we can define a “watershed” for management purposes [107]. However, if FEW capital can be conceptualized meaningfully, it may be useful in resolving the FEW scale. It may be possible to define a space where FEW capital is neither exported nor imported, and thus define an operational scale. By focusing on FEW capital, a system-level variable, rather than sector-specific commodities that may have global but diffuse footprints, one can escape the constraint of a global FEW network and bound a local or regional system. Within that boundary, exchange of FEW capital for value is meaningful, and provides a basis for evaluating the importance of potential trade-offs across sectors.

These scale dependencies and mismatches may also require novel FEW management models. Given the current trajectory towards globalization, models of centralized versus localized management are stretched beyond their original designs (e.g., [24,108–111]), and it is still unclear how that stretch is manifested within each of the FEW sectors. Were we to effectively capture FEW capital and its scale dependence, we would make a big first step toward fundamentally different resource management. The idea of “sectoral” management would lose the competitiveness of previous management, and could give way to cooperative strategies such as maximizing net FEW capital rather than competing sectoral production. Meaningfully accounting for FEW capital transactions that either directly or indirectly impact sectoral availability/sustainability has the potential to improve both.

7. Conclusions

FEW systems are unique management problems in that they inherently must deal with a multi-faceted set of physical, social, spatial, and temporal challenges. Here we make the case that these challenges are defined by the degree to which FEW resource management has become (1) specialized, (2) interconnected, and (3) interdependent. Further, by applying these criteria to a series of exemplars as test cases, we show that all three criteria are diagnostic in FEW system identification, and by implication, a lack of one or more components is disqualifying. Where there is poor communication

or coordination of FEW resources, systems face potentially inefficient inter-sectoral competition or other unintended consequences [10]. In reality, FEW management needs to respond to constant changes, both in the magnitude and in the frequency of the change. In the cases above, we have seen significant feedbacks, interdependencies, and responses to externalities, all of which demonstrate temporal variation. This dynamism suggests that any new approach to management in the FEW nexus space would always be expected to control a moving target. In principle, adaptive management schemes are dynamic [112,113]; however, the rate of approach to criticality in places such as Yemen suggests a need for as high-frequency response in evaluation, prioritization, and public policy that is itself a complex system and historically inert [114].

Based on our findings, we also advance that some of the most pressing research related to the FEW nexus is the identification of an alternative way to manage large complex systems without relying on “scale” to frame both problems and solutions [17,102]. Here we have introduced the idea of FEW capital as a potential avenue to escape the hurdles present in finding local solutions to a globalized FEW nexus, and identify a system-level indicator of status or condition. Cairns and Krzywoszynska [17] point out, however, that development of such system-level optimizations, in contrast to sector-specific strategies, will likely require significant development of a combined technical and social science inter-discipline to be successful. Given the serious implications of FEW crises and the speed with which current FEW systems may be approaching criticality, the pressure is high to develop innovative management paradigms that are conceptually rigorous as well as operational.

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Appendix A

A Primer of Philosophical Considerations for Conditions of Adequacy to Define the FEW Nexus

How does one define an idea like the FEW nexus? We understand the meaning of an idea via conceptual analysis. In conceptual analysis, our objective is to generate a clear definition of our concept that will then allow us to evaluate the connections and distinctions between our focus and other, related concepts. The gold standard in conceptual analysis is to provide a definition in terms of necessary and sufficient conditions, as doing so should capture all and only those things to which the concept applies.

“Necessary” and “sufficient” are familiar words with widely understood common meanings. However, they are also logical conditions whose rigorous meanings in conceptual analysis may seem counterintuitive when compared to common usage. For example, in common usage “necessary” may suggest a more rigorous condition, since if the necessary condition is false for a given case, it certainly disqualifies that case. However, necessary conditions do not specify all and only the cases to which the concept applies. For example, saying that someone is a “dead person” is a necessary condition for specifying a deceased president of the United States (i.e., all deceased presidents are dead), but there are lots of dead people who were never elected president. Thus, being dead is not a sufficient condition to uniquely specify the class of deceased presidents. Conversely, specifying that we are considering the President Theodore Roosevelt is a sufficient logical condition to satisfy that we are talking about a “deceased president”. In conceptual analysis, our ambition might be to start with a set

of laws, and build a series of logical or deductive conditions that would result in both a necessary and sufficient definition of our concept.

However, some concepts, due either to the wide diversity of elements to be captured by the concept or incomplete knowledge of the subject matter, can be difficult, if not impossible, to define so clearly [115]. Examples of such difficult concepts include games [115], life [116,117], and moral personhood [118], among many others. We believe that at the current state of study, the concept of a FEW system belongs to this category, and for that reason, we limit our definition to a set of adequate conditions.

Notwithstanding difficulties presented by expectations for necessary and sufficient conditions, working definitions are possible. If the study of FEW systems is to have utility in resource management, we desire robust conditions of adequacy for what constitutes a working definition of a FEW system. Such a set of conditions of adequacy would need to be both sensitive in capturing cases where the conditions are true (a FEW nexus), and selective in rejecting cases where the set of conditions are false (not a FEW nexus), and would do so without disqualifying everything or nothing. Hempel [119] developed a specific set of conditions to support selectivity and sensitivity for scientific explanation, which we have adapted for our purposes. Given that we may not be able to achieve an agreement on both necessary and sufficient conditions to define a FEW nexus, deciding that a specific case is a FEW nexus should satisfy these conditions:

- (1) That a given case is or is not a FEW nexus must be a well-reasoned consequence (given available, relevant evidence) of the conditions in the definition of the concept;
- (2) Each of the conditions in the definition of the concept must be true if the specific case is a FEW nexus;
- (3) The conditions in the definition must be generally true and not special cases of the given case; and
- (4) The conditions in the definition must be observable, testable, and relevant to the intended research.

In some cases satisfying the conditions is trivial; a FEW nexus is a logical, or “well-reasoned” consequence of an interacting nexus of food, energy, and water production systems if we define the conditions in terms of food, energy and water production. In spite of the triviality of some of the condition states, it is still critical to apply them with rigor because some systems may cryptically not be a FEW nexus.

We endeavor here to develop a set of conditions that can be used to identify those cases that are FEW nexuses, and can be diagnosed as such by practitioners and managers. The result is that a minimally adequate definition of a FEW system must be restrictive enough to focus research on coupled human–natural systems and how those systems can be managed to maintain FEW security. It must also be flexible enough to allow researchers and managers from all three sectors and at every scale to benefit from the research. These conditions of adequacy are one way to balance those desiderata.

Appendix B

Are Specialization in Production, Interdependence, and Transaction of Shortage Sufficient to Define a Unique FEW Nexus?

Historically, there are other instances of specialized production that do not produce the character of crises now anticipated in challenged FEW nexuses. For instance, the achievement of food and water security sufficient to produce food surpluses has been associated with diverse societal developments including increasingly complex economies [82,120]; non-nomadic lifestyle, high population densities, and the emergence of cities [81,82,121]; social complexity, specialization, and inequities [82,122,123], and the development of agriculture itself (e.g., [124]). Indeed, food surpluses have been implicated in enabling the development of non-essential or “prestige technologies” such as monument building and sophisticated fine arts (e.g., [125]).

It seems unlikely, however, that the stakes at the nexus of resources other than food, energy, and water, the food–fine art–water (F-FA-W) nexus perhaps, would lead predictably to the levels of violence

and critical unrest one sees in Yemen today. In strongly stratified societies, elites could inflict challenges on lower classes for the sake of their art and leisure, but this is a case requiring special conditions that even if present do not immediately translate F-FA-W nexus problems into society-wide instabilities. It may be possible for the production of art to fail to meet demand, increasing the marginal value of art, but a priori it seems unlikely that this would transact to problems in the other sectors. For it to do so would require decision makers within a community to sacrifice society-wide food security to support production of works of art. Therefore, the urgency we now see in developing innovations at the nexus of food, energy, and water is driven at least in part by the high stakes of maintaining current FEW sector enterprise. This argues for defining our nexus in terms of specialized sectors that provide essential provisioning goods and services as an additional condition on our definition of the FEW nexus. In this way, the potential to transact scarcity in essential resources across sector boundaries is both a definitional element of the FEW nexus, and also support for FEW nexus problems being different in kind from other resource problems.

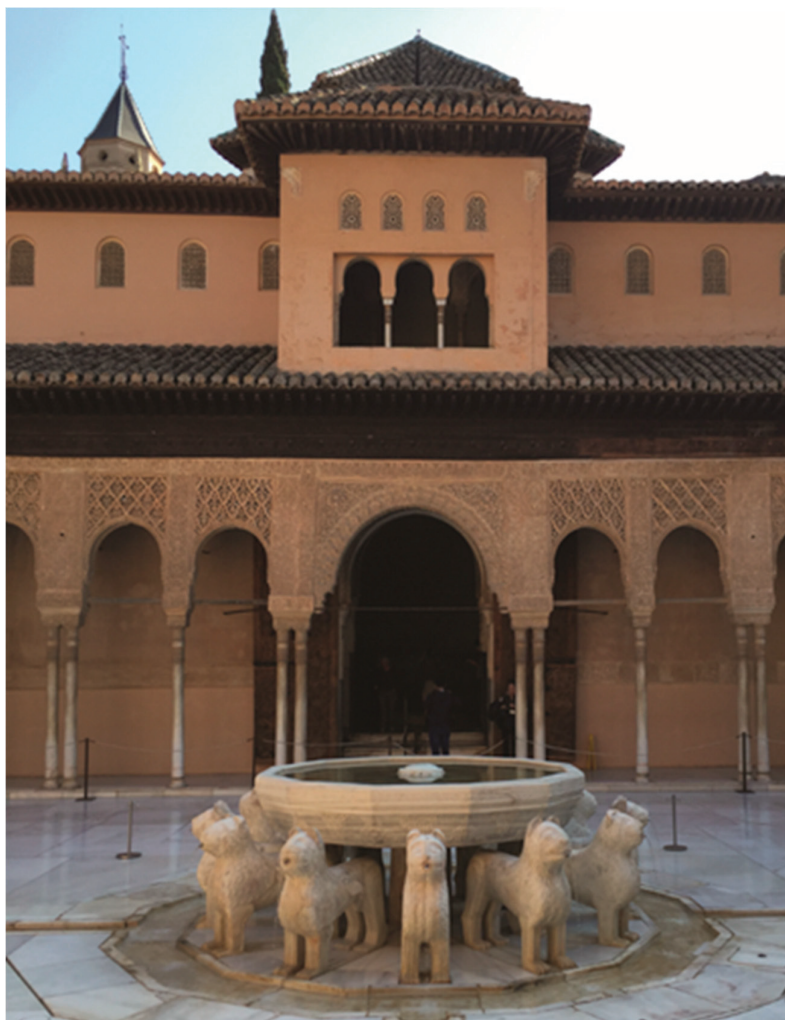


Figure A1. Hayden [125] highlights technological aggrandizement as example of art emerging among human communities that have achieved stable surpluses of food and other resources. One example is found at the Alhambra palace in Granada, Spain. In addition to intensive ornamentation throughout the palace, the Court of the Lions built in the 14th century by the Nasrid Sultan focuses on an alabaster fountain perched on 12 marble lions which originally contained a complex mechanism to allow a different lion to pour water each hour. (Photo: S.L.Katz).

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