Chapter 21
Opportunities at the Nexus

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21.1 Introduction

Management of the FEW Nexus is essential for the successful development and support of humanity. Fortunately, opportunities at the Nexus are many. As problems in one area often cause further problems in other areas, so improvements in one area often lead to benefits in other areas. Every chapter in this textbook emphasizes opportunities, problems, and tools for addressing the opportunities; we will summarize some of these key high-level FEW Nexus opportunities here.

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We began this book by noting that FEW systems provide critical consumable commodities, require massive infrastructure, are currently footprint-heavy, must be extremely accessible and affordable, and are the focus of extensive governance at all levels of human society. Food, energy, and water security are critical to healthy, prosperous, and stable human societies. Recognition of this is reflected by the prominence of food, energy, and water in the 2015 Sustainable Development Goals (Sect. 3.7) and many of "grand challenges" in science and engineering (see Sect. 1.3.3). Achieving FEW security requires the integrated management of FEW systems sustainably.

FEW systems are profoundly influenced by demographics and societal development, human behavior, economics and trade, air pollution, ecosystems, climate, and climate change. One or more of these factors are major parts of and Nexus research project and practice.

For all of these reasons, people are the center of all framings (macroscopes) of the nexus, six of which were presented in Sect. 1.4. Thus, opportunities at the nexus that change human behavior are as important as opportunities to improve science and technology.

In Chap. 17, we explored the application of nexus science to real-world problems, or practice, as carried out by both scientists and non-scientists referred to as practitioners. We noted the centrality of decision-making and how stakeholders can come together as Communities of Practice to utilize science-based tools that enhance their ability to make decisions by maximizing areas of agreement and minimizing areas of conflict. We explored a number of valuable tools that can be used to make science useful to decision-making processes, including:

- Data integration
- Integrated assessment modeling
- Methods of visual analytics
- Online platforms
- Immersive decision environments
- Tools for addressing decision-making under uncertainty
- Tradeoff analysis
- Communities of practice

The many case studies throughout this book, and in particular Chaps. 18–20, highlight the varied contexts where food, energy, and water systems interact and the many opportunities to apply science to practice. The case studies in this book also illustrate the changes to FEW systems which can be made. Many possible changes considered as positive or progressive, emphasize sustainability. A positive change

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sustains and regenerates the biophysical environment. Progressive changes provide opportunities for rewarding labor, investment, and consumption in the economic system. Positive opportunities impel and support social systems that are inclusive, open, equitable, and just in terms of race, ethnicity, gender, and age.

In this chapter, we shift from "what is" to "what might be." We begin by exploring some criteria for identifying real-world challenges that provide greater impetus and opportunity for applying integrated FEW science to real-world practice. There is the greatest opportunity for FEW Nexus applications to improve outcomes where there is a specific combination of scarcity, competition, externalities, and shared benefits. This often involves the invention of mechanisms for cooperation, reallocation of resources, sharing of private data, transactions across system boundaries, and the limited but proper role of government and law and, more broadly, the community of science and practice in the FEW nexus. We conclude with a number of case studies of Nexus work and practice that epitomize the opportunities that exist.

21.2 Situations Favorable to the Application of Nexus Science to Practice

In Sect. 1.5.2, we noted that certain situations provide greater impetus and opportunity for applying integrated FEW science to real-world practice. We now revisit the three examples of this in the context of the entire book.

21.2.1 Acute Scarcity of Two or More FEW Commodities

The aphorism "no crisis should go to waste" encapsulates opportunity for significant change that becomes possible following a natural or man-made catastrophe. Rebuilding after a storm (e.g., Puerto Rico), or creating new structures of governance after a war (e.g., the United Nations) are familiar examples. Situations of food, energy, and water insecurity are also opportunities for change. Scarcity primarily refers to the physical availability and the physical, legal, and economic access attributes of food, energy, and water security (see Sect. 3.2). These case studies provide opportunities to learn from systems approaches to resource management to build resilience.

Droughts are occurring with some frequency. Examples of droughts that have been noted in this book include California (2011–2017) (see Sects. 11.4.4 and 20.2.1), Texas (2011) (see Sect. 13.3), southern Africa (see Sect. 20.2.1), northeastern Brazil (2012–2017) (see Sect. 20.2.1), Sri Lanka (see Sect. 20.2.1), and the Murray-Darling River Basin of Australia (see Sect. 20.3.4). In each of these locations, water is critical for energy (typically for power plant cooling) and food production (especially irrigation) as well as direct consumption (which can experience increased contamination in low flows). Droughts frequently bring siloed interests in food, energy, and water into conflict. Thus, many of the case studies in Chap. 20 (Managing Human Conflicts) are triggered by droughts. As shown in Chap. 11, climate change will result in more droughts in the future.

Chapter 20 also notes that FEW conflicts are often outbreaks based on long-term simmering tensions between different interests and that droughts are an opportunity to recognize and address long-term FEW tensions and develop integrated solutions.

Because food and energy are heavily traded (Chap. 7), local disruptions in food and energy production can be mitigated by imports. However, imports can be physically denied (e.g., the oil crisis of 1973–1974), and be too expensive for many in need. These situations often highlight issues of systemic, long-term poverty, and other forms of social exclusion. In Chap. 3 (Development), we noted the importance of this issue in developing countries. In Sect. 18.4, we described the significance of poverty and exclusion in cities. In such situations, responses can recognize interactions with other components and tensions between them. For example, solutions to local disruptions in food and energy flows can include greater demands on water, arable land, and biomass, each of which creates tensions between FEW interests.

Acute shortages can also be a result of infrastructure failure. Short-term failures of electric power grids are not uncommon. Rivers are examples of natural infrastructure that move food, energy, and water. One important aspect of droughts is their ability to impact FEW transportation on rivers. During the Great Plains Drought of 2012, low water levels on the Mississippi River limited barge traffic on the river moving coal and crops.

Finally, it should be recognized that flooding, in addition to drought, can also bring about acute shortages of food, energy, and water, through direct impacts and through infrastructure impacts.

Whatever the cause of acute scarcity, it is frequently associated with a level of social unrest that motivates action by governments and international organizations. Acute scarcities were part of the motivation of the Sustainable Development Goals (Sect. 3.7). Responding to acute shortages and achieving the SDGs for food, energy, and water simultaneously is a strong motivation for integrating food, energy, and water management. In particular, repeated shortages highlight the limitation of single-sector solutions and make clear the need for integrated management.

21.2.2 Significant Externalities Arising from FEW Decisions and Stakeholder Actions

Throughout this book were have noted many examples of externalities. In Sect. 5.3.1, we noted examples such as the following:

1. applications of nitrogen fertilizers on food crops impacting local rivers and aquifers but not being reflected in the costs of the fertilizer appliers or their resultant crop product price;

2. pollutants entering aquifers due to infiltration of produced fracking water; and
3. greenhouse gas emissions coming largely from affluent, high energy-use societies, while the adverse externality (climate change effects) fall disproportionately on poor, low energy-use societies (Chap. 11).

Climate change is the highly visible global externality that is driving major shifts in the governance and practice of energy systems (primarily), but also in food and water systems. For example, coal-fired electricity generation is water-intensive compared to natural gas and renewables. Shifts away from coal-fired power generation in the USA are reducing water use. In a second example, emissions of greenhouse gases associated with food systems are leading to efforts to change agricultural practices, bolster soil carbon stocks, change food choices (especially meat-intensive diets), and reduce food waste.

There are many examples of the degradation of ecosystems and ecosystem services as externalities. Soil erosion degrading soil quality, and agricultural productivity is one example. The case study of erosion control services and conservation agriculture (Sect. 9.4) illustrates a solution with cross-cutting benefits. A shift to conservation agriculture creates benefits for food (increased productivity), as well as for water (e.g., less runoff means better flood regulation and more irrigation storage), and for energy (e.g., water available for hydropower production or more traditional biomass available).

Air pollution, water pollution, contamination of arable land, and biodiversity loss, are broad classes of externalities related to FEW systems. However, externalities only motivate action when there is a public reaction against that externality. The reaction usually begins in communities that are adversely affected by the externality, but it must include all parties to the problem in order to succeed in creating positive change.

Societies have considerable experience in developing governance strategies for externalities, ranging from rules on behavior and technology (command-and-control regulation) to market-based regulation such as pricing the pollutant or the commodity that is being used in a manner that leads to the externality (see Chap. 5). While there is little experience in addressing the FEW nexus with these strategies, sector-specific experiences provide enough confidence to many to view regulating externalities as a tool for addressing some challenges at the FEW nexus.

21.2.3 Potential Benefits to Many Communities from Coordinated Actions

Throughout this book, we have explored many instances of cooperation. Cooperation generally occurs where parties see potential benefits for themselves, even if that benefit is just the avoidance or minimization of harm. For example, Chap. 6 (International Governance) described the extensive international system established following World War II to facilitate international cooperation largely to avert a repeat of the harm caused by two world wars and the Great Depression. That system is largely responsible for the cooperation embodied in the Sustainable Development Goals (Sect. 3.7) and climate change (Chap. 11).

Chapter 5 (Economics) provides several tools to identify who gains and who loses under alternative scenarios, an important way to understand the incentives needed to attain cooperation. As noted in that Chapter, market incentives can be created to promote cooperation. Examples of incentives include assignment of private rights to property in place of property held in common, taxes on pollutants and inefficiencies, or the provision of subsidies for systemically beneficial practices.

The extensive system of cooperative international trading in FEW commodities described in Chap. 7 is largely a result of joining economic tools of cooperation with international governance structures supporting cooperation. Cooperative trading of FEW commodities supports FEW security but also achieves mutual economic benefits through the application of comparative advantage.

Chapter 10 (Infrastructure) noted that FEW infrastructures are sources of cooperation or conflict regionally and between nation-states. Chapters 18–20 of the book argue for the centrality of cities, watersheds, and conflicts as the most important contexts of application of FEW Nexus thinking. Cities are hubs of wealth, consumption, and knowledge, and have the power to dramatically alter human behavior and system function through their many economic and social connections. Watersheds are hydro-political units that integrate water governance, land use, food production, transportation, and water management, and are therefore a significant opportunity for FEW Nexus applications. Human conflicts at all scales often touch on (or are caused by) the FEW Nexus, and the presence of conflict presents great opportunities and risks for the application of Nexus thinking.

21.3 Opportunities

The core opportunity of work at the food–energy–water nexus is the opportunity to develop and improve tools in science, engineering, communication, stakeholder collaboration, decision-making, policy, governance, and conflict management that support the achievement of nexus goals. Many case studies and illustrations of this opportunity set are included in this book to inspire solutions.

New science and practice must be understood in the context of both the biophysical environment and the socio-economic-political environment. It is important to recognize that gaps in our understanding of both exist for four primary reasons. First, it is frequently, and inaccurately, assumed that sufficient use-inspired research has already been completed to support sound science-based decision-making leading to practical interventions. Second, the interactions between human activities and biophysical systems have had both positive and negative consequences for different interests. Third, the complexity of coupled human-natural systems makes separation of causes and effects difficult—every effect is also a cause, and every cause is also an effect. Finally, the scale and complexity of biophysical systems make it difficult to forecast accurately all the impacts of human attempts to influence a given biophysical system. Similarly, the complexity of multifaceted socio-economic-political systems makes it difficult to forecast all the impacts of particular changes in FEW governances on human behavior accurately.

Recognizing each of these gaps is an opportunity for future work that fills them and enables ever more effective solutions to Nexus challenges.

We will now review several interwoven themes where opportunities exist to overcome those challenges.

21.3.1 Communities of Science and Practice

Integrated research, capacity building, outreach, education, and informed private, public, and civil sectors are essential for the development of Nexus solutions. Solutions can be applied and tested locally and then used beyond regional and national borders. Such solutions require interdisciplinary cooperation, inclusivity, and transparency among stakeholders. Scientifically enabled policy, monitoring, assessment, and cooperation must complement the Sustainable Development Goals (SDGs) to make it possible to achieve them. We noted in Sect. 17.5, the value of developing effective communities of science and practice that bring diverse scientists, engineers, and non-science stakeholders together to address nexus challenges.

Interdisciplinary science has traditionally been challenging because of the narrow disciplinary training and incentives provided by academic and governmental institutions. Public funding of research has likewise been dominated by narrowly disciplinary silos for funding. While the value of interdisciplinary research has been long recognized, programs that funded such research have often been short-lived compared to the decade or more that it takes to build effective interdisciplinary communities of science. However, academic and government program opportunities funding for Nexus research have emerged. For example, in the USA, the National Science Foundation (NSF) launched a program on Innovations at the Nexus of Food, Energy and Water Systems (INFEWS) in 2016 (NSF (n.d.)) in the words of NSF:

> *The INFEWS program seeks to support research that conceptualizes FEW systems broadly and inclusively, incorporating social and behavioral processes (such as decision making and governance), physical processes (such as built infrastructure and new technologies for more efficient resource utilization), natural processes (such as biogeochemical and hydrologic cycles), biological processes (such as agroecosystem structure and productivity), and cyber-components (such as sensing, networking, computation and visualization for decision-making and assessment). Investigations of these complex systems may produce discoveries that cannot emerge from research on food or energy or water systems alone. It is the synergy among these components in the context of sustainability that will open innovative science and engineering pathways to produce new knowledge, novel technologies, and innovative predictive capabilities.*
>
> *The overarching goal of the INFEWS program is to catalyze well-integrated, convergent research to transform understanding of the FEW Nexus as integrated social, engineering, physical, and natural systems in order to improve system function and management, address system stress, increase resilience, and ensure sustainability. The NSF INFEWS activity is designed specifically to attain the following goals:*

1. *Significantly advance our understanding of the food–energy–water system of systems through quantitative, predictive and computational modeling, including support for relevant cyberinfrastructure;*
2. *Develop real-time, cyber-enabled interfaces that improve understanding of the behavior of FEW systems and increase decision support capability;*
3. *Enable research that will lead to innovative and integrated social, engineering, physical, and natural systems solutions to critical FEW systems problems;*
4. *Grow the scientific workforce capable of studying and managing the FEW system of systems, through education and other professional development opportunities.*

NSF has also engaged other parts of the US government, like the U.S. Department of Agriculture, in INFEWS funding opportunities. While the longevity of INFEWS and FEWS nexus research grants that will sustain a Nexus Community of Science is uncertain, other programs support work at the nexus from a variety of sector-based and cross-cutting perspectives such as sustainability. Thus, the opportunity for public and private funders around the world to sustain the emergent Nexus Community of Science is an important one.

In Sect. 17.5, we described the example of the Sustainable Water–energy–food Nexus Working Group of Water Future as a global nexus community of science focused on water research in support of international scientific collaboration to drive solutions to the world's water problems. Many opportunities to form similar communities exist. FEW Nexus Communities of Practice are immature at this time but emerging and evolving. We argue that communities of practice provided with appropriate tools can most effectively develop and apply solutions to nexus challenges. Providing communities of practice with useful decision-making tools and platforms frame most of the specific opportunities that follow.

Establishing a global FEW Nexus Community of Science Practice (CoSiP) would provide the foundation of a general stakeholder community that will provide a global platform to effectively address the substantial existing knowledge gaps in science, education, and governance. Such a community would also enable integrated research efforts and improve capacity building, outreach, and education efforts. Proposals for a FEW Nexus Community of Science and Practice seek to transcend regional and national borders to promote inclusive, transparent, interdisciplinary cooperation and intergovernmental in approaches between all stakeholders. Its philosophy would be supportive and complementary to the United Nations Sustainable Development Goals and be used to encourage scientifically enabled policy, monitoring, assessments, and cooperation. Indeed, locally relevant work would provide the foundation for identifying solutions to common, global problems. To achieve these ends, a FEW Nexus Community of Science Practice might offer a global platform for the nexus debate and will bridge between science, policy-making, and the general stakeholder community by:

1. Establishing a shared data platform (with national and international components) that serves all three sectors (water, energy, and food);
2. Identifying data needs and shortcomings through the evaluation of existing libraries and their ability, or lack thereof, to support multi-scale, transdisciplinary research;

3. Defining the interconnectivity of few nexus systems through a set of comparative local- and regional-scale pilot projects that test data and implement solutions in multiple locations (regional, national, and international);
4. Developing a common accounting framework that supports holistic, regional and national resource management approaches;
5. Promoting the development of innovative, high tech solutions to effectively relieve the stresses and address the challenges posed by the stressors; and
6. Establishing a set of "governance indicators" for monitoring the role and effectiveness of governance in management practices in both developed and developing countries.

These activities flow into the opportunities for future nexus work described below. Since FEW research is fundamentally applied (and also Use-Inspired), communities of science and practice can, therefore, be viewed as a foundational structure to support and sustain nexus projects. The opportunities for local, regional, and global communities of science and practice exist.

21.3.2 Defining Questions

In Chap. 12, we explored many aspects of the key to effective use-inspired FEW Nexus science is defining questions that integrate research (especially basic research) with valuable applications (see Pasteur's Quadrant in Sect. 12.2.1). Communities of science and practice provide significant help in defining nexus questions that most effectively align scientific research with the needs of stakeholders and decision-makers. Thus, in Chap. 4, we described the importance of considering the role of human behavior and adaptation in FEW systems.

However, it is crucial to remember the conversation between those that conduct research and those that apply it is a two-way conversation. While science that misses the mark of decision-maker needs is not useful (and probably not sufficiently use-inspired), a decision-maker's demand that science answer value and purpose questions lying beyond the scope of empirical science is also not useful. The FEW nexus exists in the context of both the biophysical environment and the socio-economic-political environment (see Sect. 12.2.2).

Decision science, the interdisciplinary study of human decision-making at the individual, collective, and institutional levels, can be extremely useful in connecting science to applications (see Sects. 4.3, 12.2.3, and 17.2). Decision science incorporates theories and techniques from psychology, behavioral economics, and statistics, among others, to investigate how people make decisions. This understanding can help define biophysical reach questions that will address decision-maker needs. Because the FEW Nexus is fundamentally an interdisciplinary and systems concept (and not a basic disciplinary science), researchers at the Nexus should aspire to both outcomes.

Examples of biophysical research areas relevant to decision-maker needs include:

1. Improving our understanding of soil processes, phenomena and interactions relating to soil organic matter, microbes, nutrients, and moisture to changing climatic conditions, can lead to methods that increase food yields in ways that require lower energy, fertilizer, and water inputs and with fewer negative environmental, greater farm labor safety, higher quality food, and with greater economic returns to farm operators.
2. Scaling up the integration of biophysical processes into infrastructure that supports food production (e.g., pollinator conservation and restoration, multifunctional landscapes, and urban agriculture) or productive use of wasted resources (e.g., nutrient recapture from waste streams, and heating services from cooling water in power plants [cogeneration].

Examples of socio-economic-political research areas include the following:

1. The design of stakeholder engagement processes that lead to the co-production of knowledge and science and ultimately more informed policy and management solutions.
2. Improving our understanding of the behavioral reactions of individuals to changes in FEW systems.
3. Improving our understanding of the multidimensional benefits and costs of actions in alternative uses so that scarce resources can be reallocated to "higher-value" users.
4. Non-market valuation of important nexus concerns such as **public welfare**, ecosystem values, environmental damage, and cultural values.

In Sect. 12.3, we explored the challenge of scale selection in defining questions. Nexus students should align scales of space and time in biophysical processes with those in FEW governance, resource management, and decision-making so that they can be synergistic rather than discordant. This is particularly challenging because the system processes (institutional and physical) involved in the FEW Nexus operate at varied—but specific—scales, so trade-offs between micro-, meso-, and macro-scale framings are required.

It is possible to ask many research and practice questions at the FEW nexus, but as observed by physicist Lisa Randall (2011):

> *An almost indispensable skill for any creative person is the ability to pose the right questions. Creative people identify promising, exciting, and, most important, accessible routes to progress—and eventually formulate the questions correctly.*

21.3.3 Metrics

In Chap. 13, we described the role of metrics as a bridge between science and decision-making, and ultimately behavior. Metrics are selected as means of measuring things that society values and which can be backed by science. Metrics facilitate effective stakeholder communication, engagement, and decision-making. This was illustrated in Chap. 3, where we reviewed an array of metrics used to measure progress toward the food, energy, and water objectives of the Sustainable Development Goals.

Because of the importance of metrics in thinking about issues by the public and decision-makers, society is itself molded by the utilization of metrics. As a result, different stakeholders with different objectives often favor different metrics measured at different spatial and temporal scales. The evolution of metrics from those used in the Millennium Development Goals to those used for the Sustainable Development Goals reflect the values and objectives of a larger and more diverse group of stakeholders as well as a more ambitious set of objectives.

Because the choice of metric constrains data collection and modeling, the choice of metric has major scientific implications, too. Getting the metrics right is very important. The central challenge of choosing metrics is to accurately reflect desired social outcomes for both the near-term and the long-term while maximizing the ability of science to provide them. Near-term desired social outcomes involve decision-making based on what we currently understand and value. Long-term desired social outcomes require recognizing that what we understand and value will change, and future decision-makers will be locked-in to a greater or lesser extent by the prior decisions. The student of FEW systems should guide the choice of metrics in a way that both educates the public and decision-makers about near-term decision-making and encourages them to think about future options for decision. The process of choosing metrics in FEW systems provides an important opportunity for science and non-science stakeholders to engage in discussions that profoundly shape science, communication, education, and decision-making. Thus, metrics are more than a tool to measure; they are an opportunity to frame future decisions and actions.

21.3.4 Data

In Chap. 14, we noted that adequate data tends to be the limiting factor on the quality of our estimation, modeling, understanding, decision-making, and prediction. While there is a lot of data about FEW systems, it is often challenging to locate, access, or use given critical gaps. Common data scales often do not match the scales of the decision-makers' questions. FEW systems data cover a myriad of highly specialized public and private applications, and these are voluminous, complex, and diverse with respect to data structure and standard, as well as the repositories that handle each application. Data quality, management, and rules are essential concerns for FEW systems. Fusing data for different parts of the FEW system remains a serious challenge.

However, significant advancements in management are underway. Improvements in creating and deploying low-cost sensors for onsite and remote sensing, combined with wired and wireless connectivity, and in fast computing power, give us ever better abilities to design, collect, curate, share, integrate, and utilize high-quality data.

These advancements create significant opportunities to more effectively obtain and employ data in support of better understanding and managing of FEW systems and forecasting how systems will respond to internal and external changes.

Notable examples of opportunities to advance FEW systems data include "smart" agricultural, water, and manufacturing operations that generate data using sensors, detailed supply chain data, systems databases that describe all aspects of FEW systems processes in a coherent environment, public–private and private-private partnerships on data sharing between organizations, and differential privacy tools to allow appropriate and safe access to data by various parties with various levels of access and trust.

21.3.5 Models

In Chap. 15, we reviewed the state of the art in modeling for FEW systems and the challenges in developing integrated modeling tools. In particular, we emphasize the challenge imposed upon modeling by the independent, siloed, decision-making of different actors who often prefer single-system models tailored to the details of their "silo" with only minimal consideration of the other connected systems.

However, as noted above, certain situations provide significant impetus for developing integrated models to support integrated FEW management solutions—acutely scarcities, consequential externalities, and compelling potential benefits. In such situations, successful models are based on the most important and shared needs of stakeholders, tailored to the spatial and temporal requirements of science and decision-making, and addressing system vulnerabilities and resilience to human and natural stressors. *Integrated Assessment Models* are whole-system models that aim to evaluate the systemic effects of policies and trends. Communities of science and practice can play an important role in shaping effective models. In addition to system and optimization models, much of the nexus modeling is about quantifying and analyzing trade-offs. These tools are scale and stakeholderdependent (Daher and Mohtar 2015; Miralles-Wilhelm 2016).

While models of FEW systems that can project outcomes under different possible scenarios of the future are needed for decision support, there are significant challenges and opportunities for advancing in this area of knowledge. In this book, we noted and have described a number of powerful models, including the following:

- Pacific Northwest National Laboratory (PNNL)—Global Change Assessment Model (GCAM)
- USA Environmental Protection Agency (EPA)—Automated Geospatial Watershed Assessment Tool (AGWA)
- Food & Agriculture Organization of the UN (FAO)—Land & Water Division (NRL): Diagnostic, Financial, and Institutional Tool for Investment in Water for Agriculture
- Stockholm Environment Institute (SEI) WEAP (Water Evaluation and Planning System)

- Water–energy–food Nexus Tool 2.0
- Stockholm Environment Institute (SEI)—LEAP (Long Range Energy Alternatives Planning System)
- United Nations Statistics Division—The System of Environmental-Economic Accounting (SEEA)
- The WBCSD (World Business Council on Sustainable Development) Global Water Tool
- UK DECC (Department of Energy & Climate Change) United Kingdom: 2050 Pathways Calculator
- MuSIASEM—Multi-Scale Integrated Analysis of Societal & Ecosystem Metabolism—The Flow-Fund Model
- The International Atomic Energy Agency (IAEA)—Climate, Land-use, Energy, and Water (CLEW)
- Stockholm Environment Institute (SEI)—REAP (Resource and Energy Analysis Programme)
- Agriculture and Agri-food Canada—BIMAT (Biomass Inventory mapping and Analysis Tool)

Such models illustrate opportunities for modeling, including simulation and trade-offs of FEW systems, with a focus on one or more of these primary resources at different scales.

21.3.6 Computing

In Chap. 16, we describe how the increasing volume, velocity, and variety of data required to analyze FEW systems creates challenges for traditional computational tools. Advances in experimental computer and software engineering and design applied to experimental algorithms provide an array of tools that can be selectively deployed on diverse models and data sets. The combination of systems modeling, big data, and high-performance computing power is particularly powerful because of its potential to unlock a new class of rapid interactive and exploratory immersive decision-making processes that are informed by a complete set of systems connections. This is an intuitive way for decision-makers to immerse themselves in systems and explore the connections—and it is a fundamentally transformative capability made possible by advanced computing power.

However, without careful integration of the different types of science involved in FEW system analysis, these tools can often be used as “black boxes” without looking into what is going on “under the hood.” Thus, future efforts should focus on bringing the developers and domain scientists together to develop prescriptive solutions instead of over-the-counter ones that will improve algorithm efficiencies as well as the understanding of the effects of various scenarios for specific use cases.

21.3.7 Communication

There is rarely a linear flow of science to decision-making. Decision-makers utilize science to a lesser or greater degree but are influenced by their own experiences and values, as well as the objectives of any community or constituency that they represent, before making choices and judgments. Thus, the relationship between science and decisions is a complex one. Where the products of science are more aligned with the processes and needs of decision-makers, they are more influential. Where science is more effectively communicated to and understood by decision-makers, it is more influential. How risk and uncertainty are understood and perceived can strongly influence the impact of science. Thus, two-way communication is a critical part of the application of science to practice.

Communication is a serious challenge to successful work in communities of science (i.e., scientists from different disciplines working together) and in communities of practice (both scientist/non-scientist communication, and communication between non-science stakeholders representing different communities). The core challenge of communication is to achieve two process goals: First, establish a common language and understanding of nexus issues that support communication and collaborative problem solving and solution development by diverse stakeholders, and second, implement processes that facilitate communication between different stakeholders. Fortunately, there are several examples of how to address this challenge, such as a research question, a metric, a modeling outcome, or a decision-making support tool.

Throughout this book, we have seen many examples of communication processes;

1. University-based research initiatives frequently hold stakeholder workshops. For example, The Texas A&M University System Water–energy–food Nexus Initiative, which focuses on Decision Support for Water Stressed FEW Nexus Decisions, held a 2018 “Stakeholder Information Sharing and Engagement Workshop” involving “over 70 stakeholders drawn from the water, energy, and food sectors in San Antonio and surrounding region.” Facilitated small-group sessions were held to obtain stakeholder input on research questions to be asked, and on limitations and opportunities for stakeholder engagement on WEF nexus-related work (Rosen et al. 2018).
2. The Food and Agricultural Organization of the United Nations (FAO) operates multi-stakeholder processes at the level of countries to “decide what issues to focus on and what actions to take” and is “fundamentally about participatory decision-making and information sharing at the country level.” One rationale is, “If local people take ownership of all stages and levels of decision-making, development activities are more likely to build on local strengths, meet local needs and priorities, and foster self-determination and sustainability.” (FAO website).
3. The International Joint Commission (see Sect. 19.2.3) which oversees issue related to shared waters on the border between the USA and Canada has a Great Lakes Science Advisory Board which engages a diverse set of scientists to provide advice on research and scientific matters, including science priorities

and research coordination. The IJC also conducts a binational poll to understand stakeholder concerns and aspirations for water resources.

4. The Intergovernmental Panel on Climate Change (IPCC) (Chap. 11) is tasked with engaging the scientific community to synthesize and communicate the current state of scientific understanding in three areas (physical science, impacts, adaptation and vulnerability; and mitigation). Each of the reports includes a Summary for Policymakers (SPM), which is drafted first by scientists and then reviewed by governments who provide feedback. A second draft by scientists is later discussed, sentence-by-sentence, in a meeting that includes delegates from government and observer organizations and scientists.

Communication between different stakeholders often benefits from the use of a third-party neutral facilitator to help people have more productive conversations and meetings, as illustrated in Chap. 20 (Managing Human Conflicts). As noted in Sect. 17.1, the two-way, iterative engagement between producers and users of scientific information builds trust, facilitates social learning, and increases the credibility, saliency, legitimacy of research.

It is often surprising to non-scientists that scientists with different disciplinary backgrounds have great difficulty communicating with each other. Scientific disciplines develop languages that have exact meanings to the practitioners of each discipline. Disciplinary scientists can become intellectually siloed within disciplinary academic departments and profession advancement decisions based on publications in disciplinary journals where adherence to shared definitions of terms is essential. Thus, interdisciplinary science requires agreement on a common language and reference shared by scientists in different disciplines. Better interdisciplinary communication between scientists is therefore essential for FEW research.

Further, this common language must be shared and understood by practitioners and decision-makers to facilitate communication with them. Often scientists can adopt the general terms of practitioners and decision-makers. In Sect. 11.3, we described an approach developed and used by the Intergovernmental Panel on Climate Change to communicate scientific uncertainty and risk, using terms that are generally accessible (see Table 11.1). Given that understanding and addressing uncertainty and precision of information and decisions is essential for making high-quality decisions (Sects. 1.5 and 17.4), this approach has valuable lessons to the communication of FEW system science.

Visualizations of FEW nexus data, projections or predictions, and other scientific results (see Sect. 17.3.3) can serve as a decision support system to decision-makers and stakeholders with less knowledge about the underlying interconnected components. When using visualizations, it is important to identify the best means of visualization and modeling systems to represent stakeholder interests and provide stakeholders with the greatest understanding and decision-support. Online platforms (see Sects. 17.3.4 and 17.6.2) and immersive decision environments (see Sect. 17.3.5) are examples of powerful communication tool we provide significant opportunities for more effective communication. Visual communication is a powerful common language that nearly all humans share, across disciplines and other boundaries.

21.3.8 Collaborative Solutions

Throughout this book, we have seen challenges at the nexus in terms of balancing demands for food, energy, and water against a wide array of consequences—environmental, human, economic, cultural, and other impacts. FEW management is usually a matter of weighing trade-offs. Successful solutions meet societal demands for food, energy, and water while minimizing adverse effects. In Chap. 20 (Managing Human Conflicts) we described how conflicts among food, energy, and water sectors range from individuals to global in scale with minor changes to one sector having profound impacts in other sectors. However, defining the scale of connection between all three has been challenging, unpredictable, and oftentimes, uncharted. Conflicts can be exacerbated by climate change, ecosystem degradation, weak institutions and governance, population growth, and transboundary issues.

In Chap. 20, we described how constructively engaging stakeholders to participate in improving nexus relations and reducing conflict and develop solutions that all, or most stakeholders can agree with. How stakeholders are engaged can be specific to a particular scale or reach across a plethora of continuums including, but not limited to, negotiations, public involvement in regulatory policy development, community preparedness workshops, and global agreements to implement change.

Developing viable solutions to cope with conflict in the nexus is critical to future management, policy development, and human interaction with the environment. In our considerations of communities of practice, defining questions, and communications, we have already addressed many opportunities that help create a collaborative framework for Nexus projects that lead to solutions likely to be acceptable to a larger set of stakeholders.

There are, however, challenges in the development of cooperative solutions:

1. Identifying potential win-win situations;
2. Convincing parties that benefits are both real and worth of their engaged cooperation;
3. Not allowing the interests of important stakeholders without political and economic power to be marginalized by powerful stakeholders; and
4. Governance systems (e.g., institutions and treaties) that are siloed in a manner that artificially limits, rather than supports, cooperation across the separate sectors.

Fortunately, there are many opportunities to advance collaborative solutions and many tools to utilize.

Collaborative governance (see Sect. 20.3.4) is a class of processes that advance collaborative policy and regulation as a solution. Collaborative governance engages stakeholders in making, implementing, and enforcing public policy. Techniques of collaborative governance include "deliberative democracy, e-democracy, public conversations, participatory budgeting, citizen juries, study circles, collaborative policymaking, and other forms of deliberation and dialogue among groups of stakeholders or citizens" (Blomgren-Bingham et al. 2005).

Collaborative geodesign (see Sect. 17.6.1) is an example of a collaborative tool that engages stakeholders in landscape design using a tool that interactively lets them test and receive feedback for different design decisions. The benefit of this approach is that the stakeholders can immediately see the impact of their design decisions on biophysical and social indicators. Collaborative geodesign is a step forward to initiate discussions among stakeholders and domain scientists. Thus, the actual parties (i.e., stakeholders) that are affected by the decisions have the opportunity to communicate their concerns with the scientific community as well as the policymakers to make better and more realistic design decisions.

21.4 Case Studies in Opportunity

21.4.1 Watershed Integration Case Study

Globally, watersheds are diverse in terms of their scale, resource uses, and governance structures and they are also subject to different pressures from interactions at the FEW nexus. Watersheds often share multiple municipal, regional, or national borders, and this characteristic suggests the need for systems of cross-border governance and resource management. The challenges for cross-border governance vary widely because of the differences in geological, ecological, economic, and sociopolitical contexts. While the challenges are real, so are the opportunities to use watersheds to solve Nexus problems. Certain geographic and socioeconomic conditions provide greater opportunity, momentum, and political will for applying the integrated scientific study of the FEW nexus to real-world practice at the watershed scale.

In the context of watersheds, building institutional capacity for transboundary governance that is inclusive, equitable, and well-coordinated is likely to be more effective in the context of abundant water resources (not scarce resources)—such as the success of the Great Lakes Compact in the Great Lakes region of North America (Sects. 8.1.1 and 19.2), where significant success has been achieved. However, there are also numerous governance issues that may impede coordination in addressing FEW nexus challenges under conditions of resource abundance—specifically, the issues identified above in Table 19.4, including:

- Institutional capacity for effective decision-making;
- Scale of the watershed;
- Inclusiveness in decision-making;
- Coordination in integrated action;
- Distributional issues related to benefits or negative externalities;
- Heterogeneity among stakeholders and their objectives;
- Political system, and associated trust in its efficacy;
- Social mobility across socioeconomic strata; and
- Political economy and alignment of relations with law, custom, and government.

There exist many opportunities to advance FEW nexus science and application in the context of watershed management, especially in the following areas:

- Building communities of science and practice, especially where watersheds require cross-border coordination and governance;
- Defining scientific questions that address the needs of decision-makers and the capabilities of the scientific community;
- Using participatory processes of choosing metrics and indicators to engage stakeholders in both the scientific and non-scientific communities in discussions the advance knowledge, communication, education, and decision-making;
- Using new abilities to collect, integrate and utilize vast amounts of data for robust science at the nexus of FEW systems in watersheds;
- Developing better models that capture the complex interactions of FEW systems and accurately project future outcomes under defines changes to the system;
- Connecting upstream and downstream communities;
- Utilizing significant advances in computing and data analytics to develop models and machine-learning technologies in a manner that generates useful results to researchers, stakeholders, and decision-makers;
- Delivering more effective communication about FEW systems and the trade-offs inherent in decision-making regarding policies and other actions to change systems for more desirable outcomes;
- Developing and deploying collaborative solutions with diverse groups of stakeholders from both the scientific and non-scientific communities;
- Achieving global food, energy, and water security, in all their aspects, for all people, in a sustainable manner that does not undermine the functional integrity of ecosystems.

Issues related to the FEW are complex, particularly in watersheds that are characterized by resource abundance, and that share cross-border governance. FEW nexus approaches offer many opportunities for the twenty-first-century researcher, student, and practitioner to explore trade-offs at the nexus of FEW systems governance, particularly under conditions of resource abundance.

Looking ahead, now that you are equipped with a systems perspective and toolkit, how can approaches to understanding integrated food–energy–water systems help address problems at the nexus of FEW systems? How can such approaches contribute to solutions under conditions of resource abundance? How can such approaches be useful in a watershed context that is characterized by cross-border governance? How can a new framework for transboundary governance of the nexus of FEW systems in watersheds address emerging challenges, even in conditions of resource abundance?

21.4.2 Environmental Governance Case Study

In 1994, US President Bill Clinton signed Executive Order 12898, requiring federal agencies and grantees to consider environmental justice in their decision-making. While EO 12898 has its limitations and could be revoked by another president at any time, few dispute its importance in raising awareness about environmental justice. In a similar fashion, any president could issue an executive order requiring consideration of food–energy–water nexus impacts, perhaps as part of NEPA.

NEPA has its limitations, chiefly because it mandates procedural steps but not substantive outcomes. In other words, the environmental impacts of various alternative project proposals must be considered in the process, but the sponsoring federal agency is not required to select the proposal option that is least detrimental to the environment. However, NEPA precedent provides some latitude for the executive branch to take a more substantive interpretation of the law. Forcing FEW considerations into NEPA by executive order, then, could be highly instrumental in bringing nexus analysis to the forefront of US policy.

A second means of incorporating FEW consideration into US policy would be to reform the Clean Water Act and Safe Drinking Water Act to require nonpoint source pollution prevention. Doing so would strengthen existing voluntary initiatives to install riparian buffers or sediment traps, or to incorporate manure into farmland using ecologically appropriate methods.

Still another option would be to form a National Council on the FEW Nexus, like the Council on Environmental Quality. The Council could guide key agencies regulating energy, food, and water in coordinating policies, identifying unintended consequences, and reducing inefficiencies and conflicts among FEW policy and laws. Similar structures could also enhance the coordination of the individual FEW sectors.

At the state and local levels, laws and land use regulations designed to protect specific economic sectors, increase energy security, or support local agriculture can directly conflict with environmental goals. Right to Farm laws designed to protect farmers from nuisance suits can hamper water conservation and pollution reduction. At the same time, better financial support for county-based Soil and Water Conservation Districts and similar institutions involved in outreach about best practices in agriculture could decrease the externalities of agriculture on water resources. In addition, policies supporting technical approaches that make farms more energy-efficient and reduce the carbon footprint of food production could help. Expanding these policies to include explicit consideration of energy and water flows and costs would improve the models and increase the resilience of food regulations.

Changes in political administrations can impact environmental regulations. Regulations may be perceived as overly burdensome to industry and detrimental to the economy. FEW regulations are no exception; in early 2018, the EPA sought public comment on whether it should clarify or revise its interpretation that discharges to surface waters via groundwater should be subject to regulation by the CWA. This debate strikes at the larger question about how to best incorporate changing scientific knowledge into law and policy. We invariably assign rights based on our current understanding of the world. When science proves that understanding to be inaccurate, significant legal, political, and practical challenges result.

One benefit of federalism is that when states fail to act, the federal government may step in, and vice versa. When federal administrators decrease protections or support for water, renewable energy, or climate change mitigation that would protect FEW resources, state governments may step in to counter those moves. California's persistent engagement in climate discussions, even as the Trump Administration withdrew at a national level, is one important example. Other actors such as basin commissions, watershed associations, energy cooperatives, and third-party certification programs can fill the gap with forward-looking initiatives that target specific problems. For these efforts to bear fruit, policymakers must be willing to listen to the scientific community, and scientists must be able to communicate the results of their work in language accessible to policymakers and the general public.

21.4.3 Data Fusion Case Study

The FEWSION™ project (https://fewsion.us) is a data fusion effort funded in 2016 by the National Science Foundation's interdisciplinary INFEWS program (Innovations at the Nexus of Food Energy and Water Systems). FEWSION brings together a large number of academic and government data sources to describe the commodity flows in the US FEW system in a single seamless dataset. This data enables place-based researchers and those studying a single component of the system to place their work within the broader perspective of the entire FEW system.

This data fusion requires expertise in a large number of distinct datasets and data formats, along with expertise in the data science tools for upscaling, downscaling, cross-walking, and harmonizing voluminous and heterogeneous datasets into a single data structure. This process involves ingesting a large number of Level-0 (raw source) datasets, their transformation into a single large Level-1 (coherent integrated) dataset, and then the application of quality control tools to produce reliable Level-2 (inspected and quality controlled) datasets. This process is accomplished using a scientific workflow implemented using Python language, allowing the reproducibility of the dataset. The resulting dataset size is measured in Petabytes, and its calculation required high-performance computing (HPC). This data resource features documentation, a data model, metadata, a codebase, and both publicly available extracts of the data and also privately controlled source datasets, along with visualization and data download services.

The FEWSION Database™ 1.0 includes some of the following data types:

- 43 Commodity flow categories, based on the "SCTG+FEWSION" code scheme
  - Food and Beverages (for people)
  - Agricultural Products
  - Fuels (Natural Gas, Diesel, Gasoline, Coal)
  - Electricity
  - Water Use
  - Surface water flows and transfers
  - … and all other major commodity types
- Flows between 3,143 US Counties and 8 Foreign Regions
- Seven transportation modes (Pipeline, Power Grid, Rail/Train, Road/Truck, Water/Ship, Air/Plane, Mixed)
- 2012 annual data

The FEWSION Database™ 1.0 utilizes some of the following data inputs:

- U.S. Census Population Data
- U.S. Census Economic Census
- Bureau of Labor Statistics
- U.S. Geological Survey (Water use census, surface flows)
- U.S. Department of Agriculture National Agricultural Statistics
- U.S. Department of Agriculture Economic Research Service
- U.S. Census Commodity Flow Survey
- Oak Ridge National Laboratory/U.S. Department of Transportation Freight Analysis Framework
- U.S. Energy Information Administration
- U.S. Environmental Protection Agency
- U.S. Department of Homeland Security
- U.S. Department of Agriculture CropScape
- DHS HIFLD Open Data
- National Renewable Energy Laboratory ReEDS Energy & Power Flow Data
- National Renewable Energy Laboratory ReEDS Water Withdrawal and Consumption Data
- U.S. Foreign Trade Data
- Global Water Productivity Data
- Water Footprint Network
- Academic surface water flow models
- Academic surface water transfer statistics
- Academic electrical power flow models

FEWSION provides an online publicly accessible visualization and data search and retrieval system called FEW-View™. FEW-View™ 1.0 allows a user to select commodity types and units, choose locations, and visually map the supply chains. Users can benchmark and compare their community's FEW usage or footprints with other US communities. Users can view analytics that describes their supply chain network-like resilience or circularity metrics. Users can print out reports for their communities' supply chains, and can directly download the data that they see on their screen. The map interface looks like this (Fig. 21.1).

Visual analysis and exploration is one of the most effective strategies for orienting both technical analysts and stakeholders within a systems context. People have a limited capacity to grasp systems of connections, but people are relatively adept at visual comprehension and exploratory analysis. However, before a user can employ this kind of analysis tool, the user must be trained. Even relatively simple interfaces require significant training and experience. In order to streamline the user's onboarding to the tool, FEW-View™ utilizes a combination of science art and narrative storytelling, followed by preconfigured scenario maps, to ease the user into the interface. An example scenario follows below (Fig. 21.2).

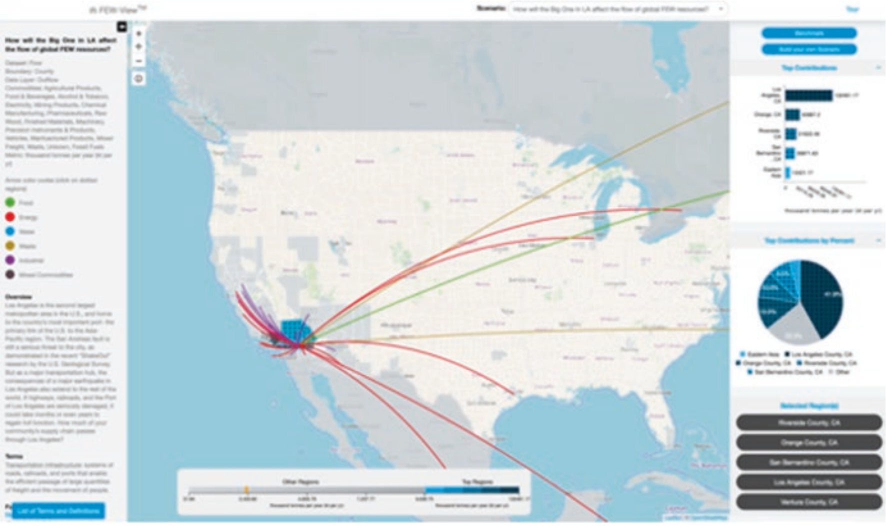

Fig. 21.1 Screenshot from the FEW-View™ 1.0 mapping interface. Used with permission from the authors

Key Points

- Certain situations provide greater impetus and opportunity for applying integrated FEW science to real-world practice, such as:
  - Acute scarcity of one or more commodity.
  - Significant externalities from FEW decisions and actions.
  - Potential benefits to many communities from coordinated actions.
- There exist many opportunities to advance FEW nexus science and application, especially in the following areas:
  - Building communities of science and practice;
  - Defining scientific questions that meet the needs of decision-makers and the capabilities of the scientific community;
  - Using the process of choosing metrics to engage science and non-science stakeholders in discussions that profoundly shape science, communication, education, and decision-making;
  - Using new abilities to collect, integrate and utilize vast amounts of data for stronger science;
  - Developing better models that capture the complex interactions of few systems and accurately project future outcomes under defined changes to the system;
  - Utilize significant advances in computing to use data and run models in a manner that generates useful results to stakeholders and decision-makers;
  - Carry out more effective communication about few systems and the choices in policies and other actions to change systems for more desirable outcomes;

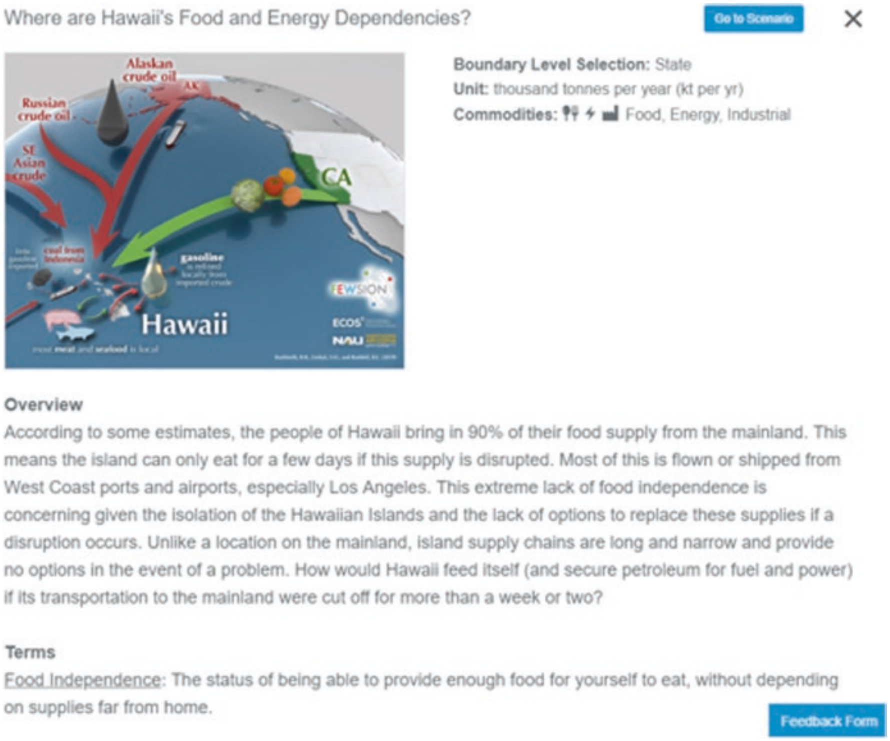

Fig. 21.2 Screenshot from the FEW-View™ 1.0 onboarding scenario interface, for Hawaii's food and fuel supply chains

  – Develop and deploy collaborative solutions with diverse science and non-science stakeholders; and
  – Achieve food, energy, and water security, in all their aspects, for all people, in a sustainable manner.
  – Share data, tools, and knowledge and disseminate using the ever-increasing e-space.

- A requirement to include food–energy–water nexus considerations in analysis carried out under the U.S. National Environmental Policy Act (NEPA) could increase consideration of externalities of decisions on nexus resources.
- Data fusion, modeling, and visualization systems (like FEWSION) provide a useful and accessible interface between scientists, stakeholders, decision-makers, and the public—if they are carefully implemented with the user community in mind.

Discussion Points and Exercises

1. Now that you are armed with a FEW systems perspective and toolkit, how will you use these Nexus opportunities to make the world a better place?

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