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Review

Why Do We Need Food Systems Informatics? Introduction to This Special Collection on Smart and Connected Regional Food Systems

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Abstract: Public interest in where food comes from and how it is produced, processed, and distributed has increased over the last few decades, with even greater focus emerging during the COVID-19 pandemic. Mounting evidence and experience point to disturbing weaknesses in our food systems' abilities to support human livelihoods and wellbeing, and alarming long-term trends regarding both the environmental footprint of food systems and mounting vulnerabilities to shocks and stressors. How can we tackle the "wicked problems" embedded in a food system? More specifically, how can convergent research programs be designed and resulting knowledge implemented to increase inclusion, sustainability, and resilience within these complex systems, support widespread contributions to and acceptance of solutions to these challenges, and provide concrete benchmarks to measure progress and understand tradeoffs among strategies along multiple dimensions? This article introduces and defines food systems informatics (FSI) as a tool to enhance equity, sustainability, and resilience of food systems through collaborative, user-driven interaction, negotiation, experimentation, and innovation within food systems. Specific benefits we foresee in further development of FSI platforms include the creation of capacity-enabling verifiable claims of sustainability, food safety, and human health benefits relevant to particular locations and products; the creation of better incentives for the adoption of more sustainable land use practices and for the creation of more diverse agro-ecosystems; the wide-spread use of improved and verifiable metrics of sustainability, resilience, and health benefits; and improved human health through better diets.

Keywords: assessment workflow; informatics; ontology; knowledge graph; semantic web of food (SWoF); internet of food (IoF); food justice; resilience; democratization; sustainability

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1. Introduction

We begin by providing a conceptual framing of food systems and associated challenges within rapidly changing global conditions and politically contested food systems policy issues. The daunting list of challenges and pressures that have exposed shocking vulnerabilities in our food systems include Putin's invasion of Ukraine; the COVID-19 pandemic; climate change and associated fires, floods, and droughts; racial and economic inequality; and profound polarization along several axes across scales, from among global hemispheres to localized rural-vs-urban divides. In concert, these pressures threaten human health and wellbeing and the sustainability of the natural resources upon which we rely for our food. These realizations have spawned a burgeoning scientific literature on the alarming long-term trends relative to food system environmental footprints, shortcomings in outcomes for people, and mounting systemic vulnerabilities to shocks and stressors ([1–6] and many others). Moreover, see [7] and Campbell et al. 2022 [8], who report that more than two dozen food system publications have appeared in the past two years.

An important theme emerging in this recent literature is what [9] terms "knowledge controversies"—deficiencies in access to information and *not* "simply controversies over competing values or interests"—in their call for new, pluralistic "knowledge–policy" interfaces for food systems. Similarly, [8] calls for "greater efforts in collecting, collating, and curating the data needed for decision making . . . " There has been significant progress in generating relevant data on food and on agricultural production, particularly precision agriculture [10–12]. However, integration across data in ways that make useful information widely accessible to diverse food system stakeholders remains elusive [4,13].

Definition: what do we mean by "food systems"? Our point of departure in this review is one of the earliest published definitions of a "food system" [14] (also see [4]): "the set of *activities and relationships* that interact to determine what, how much, by what method, and for whom food is produced and distributed", with emphasis added for reasons explored in greater depth below. More recently, [4] (p. 8) concluded that "The growing demand for a more holistic 'food systems approach' to policy making is based on the realization that there are potential synergies and trade-offs between food security and nutrition, livelihoods, and environmental sustainability"; continuing that "This complexity makes it hard to generalize, and highlights the importance of evidence: while it is easy to speculate about possible synergies or trade-offs, it is imperative for policy makers to scrutinize those hypotheses before using them as a basis for policy decisions". More generally, it also is necessary to ground our conceptual framing to encompass a deeper "systems approach to address underlying structural problems and system dynamics that affect production, people, and the planet (i.e., sustainability)" [15].

Challenges in linking knowledge with action to transform food systems. Through the food systems "activities" lens, there are particular conceptual framing challenges regarding food system boundaries, especially as these relate to drivers and disruptors arising outside the food and agriculture system. Nexus framing may be a way to a depict this, e.g., food x water x climate x energy or food x poverty x hunger x disease; "syndromes" also may be a way to make these "nexus" ideas more dynamic; either way, these linkages become a strong element of our rationale for a convergence approach harnessing informatics to enhance effectiveness in participation, inclusion, and engagement.

There are further correlated challenges when viewed through the food systems "relationships" lens. Consensus on causal mechanisms and public policy goals in food systems has been elusive (in part) because these multiple links involve systems of numerous components, in which major interactions can be non-linear, complex, and interdependent; interventions aimed at affecting components and outcomes also are numerous, complex, and interdependent; implementation of interventions requires partnership and concerted cooperation across multifarious organizations and scales; key phenomena (e.g., both socioeconomic and ecological processes) display emergent properties, meaning that there may be no clear "line of sight" linking intervention points (say in fields, farms, or firms) with desired impacts (viz, poverty reduction); and prospects for desired impacts are context dependent [16].

Given the nature of their many challenges, food system transformation for greater resilience, sustainability, and equity means tackling "wicked problems" [17], requiring multiple sources of expertise and information spanning many disciplines and involving multiple individuals and organizations with a stake in outcomes, often with conflicting interests and values and even disagreeing on what the problem actually is or whether there is a problem at all. Schuler [18] applies pattern language (introduced in [19]) to refute the assertion in [17] that "Every wicked problem is essentially unique." Clark et al. [20] demonstrate the need for investment to build negotiation support capacity when multiple knowledge sources are essential and when multiple divergent stakeholder interests must be engaged. Anderies et al. [21] draw a similar distinction between what we call the "textbook" natural resource management problem—singular welfare goal and optimal allocation by a social planner with considerable certainty about cause and effect—with a "real world" policy problem involving multiple interrelated and contested goals, complexity of actors and social dilemmas, poorly understood (or missing) institutional capabilities, and considerable uncertainty in a complex dynamic system with multiple interactions, feedbacks, and somewhat chaotic patterns produced by external drivers.

Introduction to the special collection. The focus of this special collection is a growing wave of innovations that hold potential to address underlying deficiencies in data and analytical capabilities so that innovation and sustainable transformation of our food systems can be accelerated in the face of growing threats. The scope of the collection spans informatics and data science innovations in network engagement, analytics, and translation to enable equitable access to better data and assessment capabilities for use by any and all food system actors and advocates, facilitating information discovery for evidence-based negotiation support and co-creation of innovative solutions. Much of what is presented was developed through application, from use cases focused on food system challenges and opportunities. Topics include new conceptualizations related to informatics, innovative information exchange standards, such as ontologies and controlled vocabularies, knowledge graphs, generalized workflows, and data governance standards, as components of a smart and connected food system platform. The overarching purpose is to enhance equity, sustainability, and resilience through collaborative, user-driven experimentation within complex food systems toward a set of guideposts: diverse agroecosystems, circular economies, and equity-based cultural norms.

Relationship of this collection to existing literature. Within the existing literature, many studies take a partial approach to food system sustainability and resilience, covering some aspects (economic, environmental, or social) but missing others, thereby failing to provide a comprehensive framework. Among these, some use top-down, static approaches. Other innovations in data science that can be monetized tend to be proprietary, and hence exclusive (and unpublished). We emphasize articles that take an open approach to data and research, seek interoperability among linked data and tools, and strive for holistic, comprehensive, and dynamic approaches to challenges and opportunities to support food system sustainability. This encompasses tools for systems analysis as well as community engagement, incubation of entrepreneurship, and legal aspects of data sharing (IP, privacy, and data ethics). The articles in this collection span a wide range of the food system domain, although they are not exhaustive, as there are other relevant topics, such as food waste [22], that are not well-represented. These articles, and others in the emerging body of literature, do not yet constitute a comprehensive food systems informatics approach. Rather, many take the form of use cases and thus show how information technology can address a wide range of food systems questions and challenges, and, therefore, collectively and cumulatively point toward a complete approach (Figure 1).

1. "Early Ethical Assessment: An Application to the Sustainability of Swine Body Scanners" [23].
2. "PestOn: An Ontology to Make Pesticides Information Easily Accessible and Interoperable" [24].
3. "Workflows for knowledge co-production: Meat and dairy processing in Ohio and Northern California" [25].
4. "Exploring Social Media Data to Understand How Stakeholders Value Local Food: A Canadian Study Using Twitter" [26].

5. "Using systematic planning to link biodiversity conservation and human health outcomes: a stakeholder-driven approach" [27].
6. "Design and Implementation of a Workshop for Evaluation of the Role of Power in Shaping and Solving Challenges in a Smart Foodshed" [28].

Use cases included in this collection (see section 1):

(1) Ethical assessment of technology (Thompson et al.)

(2) Pesticide use (Medici et al.)

(3) Meat and dairy processing (Hollander et al.)

(4) Consumer choice (Chicoine et al.)

(5) Built environment (Huber et al.)

(6) Political and economic power (Hyder et al.)

(7) Food system informatics (this article)

Use cases in development *(see section 3):*

(A) Food supply chain diversification

(B) Food access for hungry people

(C) Food for better health

(D) Working landscapes for regional resilience

(E) Food system governance

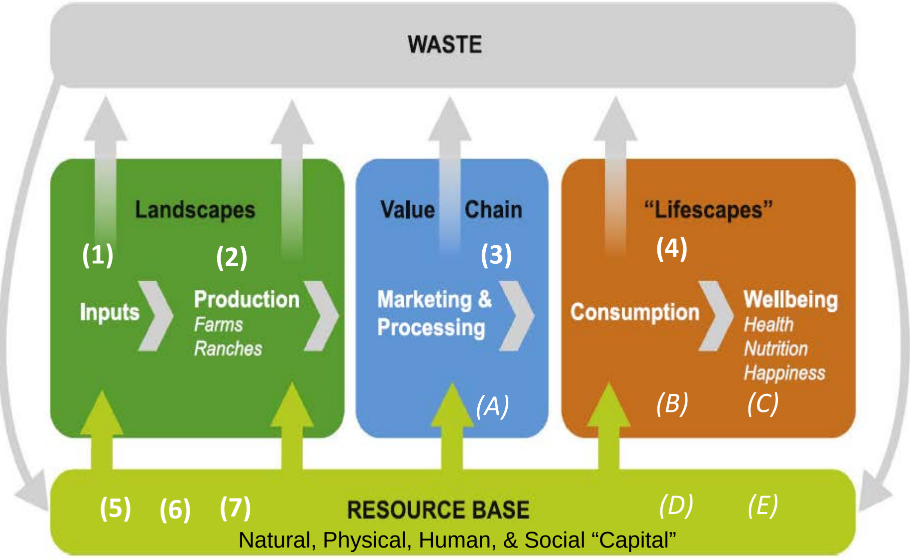

Figure 1. Use cases in this collection situated within a food systems schematic. Figure adapted from [16]. Citations to articles in this collection: [23–28].

Technology assessment. New technologies that require, interface with, or build upon informatics frameworks are opportunities to extend capabilities in either of the two generalized application domains discussed below in Section 3. For example, the ethics of using swine monitors delves into both the activities involved with pork production and factors that influence the relationships between producers and consumers [23]. Work to create interoperability among pesticide datasets is meant to improve the collaboration between producers and regulators and ultimately improve the safety and sustainability of pesticide use in agriculture [24]. Additionally, social media may be an untapped source of data and insights into the varying attitudes, interests, and values surrounding local food both within and across communities [26].

Section 1 has delineated conceptual and operational challenges intrinsic to food systems and motivates both this review and the articles in the special collection. Building on the operational definition of food systems and contextualization within our introduction of contemporary issues, we now move on to our motivating methodological question that unites all the articles in this collection: Why do we need Food System Informatics? Section 2 introduces key concepts, methods, and definitions, including our definition of the new term "food systems informatics" and links them to relevant informatics methods. Section 3 discusses promising applications to regional food systems, continuing development and improvements in methods and approaches, and their potential impacts for systemic sustainability and resilience, for which social justice and equity are requisites. In Section 4, we discuss promising potential outcomes and impacts of the development of food systems informatics platforms. Finally, in Section 5, we conclude with observations on next steps and policy implications, including some significant caveats about application of these informatics platforms for our food systems.

To sum up our purpose: this paper is intended *both* as an introduction to this special collection *and* to the new field of food systems informatics (FSI), which is defined in Section 2. Taken together, this collection also serves the bigger purpose of introducing the new field. The other articles in the collection illustrate examples of the application of these tools to specific parts of food systems. The present paper is intended to show how these components, ongoing work, and future use cases can create a comprehensive food systems informatics platform incrementally and cumulatively. One insight from years of work is that a top-down approach to food systems as a whole is not feasible. Thus, this bottom-up approach is necessary to make progress while producing use cases as practical intermediate outputs. At the same time, we feel the overall context and framing of this review article is necessary for those incremental, partial use cases to cumulatively create a more comprehensive food systems informatics platform. The articles we cite in this review span many very broad literatures; they were selected by our diverse author team to represent the literatures we have found most useful in the development of this new field. Taken together with the other articles in this collection, the work reviewed here is motivated by two overarching research questions:

1. How can the complexity intrinsic to food systems be managed more effectively by public policymakers, food system advocates, and private enterprises, including farmers and processors?
2. How can quantitative benchmarks be developed and updated dynamically to understand tradeoffs across objectives and facilitate negotiation, mediation, and innovation among interest groups in searching for solutions and monitoring progress?

2. Methods: Definition and Data Science Tools

Food systems informatics (FSI) is an emerging transdisciplinary field that is distinguished by the following characteristics:

- Development and application of data science and information and communication technologies (ICT) to food, agriculture, and human wellbeing from a holistic, systems perspective.
- Use of data science and ICT to include and engage the full range of diverse food systems stakeholders and their knowledge, expertise, and epistemologies.
- User-driven and science-informed portrayal of food system activities and human relationships that interact to determine what, how much, by what method, and by whom food is produced, processed, distributed, and consumed and the associated human health outcomes.
- An overall goal of building knowledge infrastructure necessary to reveal, understand, and influence food system structure and function spanning scales from molecular to planetary and nanoseconds to centuries.

Definition: Food systems informatics. FSI applies data science and informatics with the engagement of diverse stakeholders and forms of knowledge to portray activities and human relationships that determine what, how much, by what method, and by whom food is produced, processed, distributed, and consumed, and the associated health outcomes, socioeconomic consequences, and environmental impacts and vulnerabilities. FSI has broad applications in building diverse partnerships and innovative programs, stimulating innovation and entrepreneurship, and shaping public policies and other initiatives to influence food systems across multiple scales, while balancing tradeoffs across issues and objectives and benchmarking and monitoring progress toward greater equity, sustainability, and resilience.

This definition was developed collaboratively by the coauthors in the course of our collaborative work; it was workshopped and refined in a workshop at the Center for Environmental Policy and Behavior of the University of California Davis in October 2021. We feel this multi-dimensional definition is necessary to fit our purposes of engaging food systems stakeholders inclusively and to address food systems' complexity in a practical way. FSI is distinguished from the related and complimentary concept of *food informatics* [29] in its focus on the entire complex, coupled social-ecological system from sources to consumption to health and environmental outcomes and impacts and interactions, as opposed to the complex and widely varying composition and preparation of what people eat.

In focusing jointly on human wellbeing and environment health and the interactions between them, endeavoring to provide negotiation support to multiple interests and to link multiple knowledge sources with collective action spanning many conflicting interest groups, our approach to FSI has its intellectual roots in sustainability science [30] and is informed by the literature on coupled systems [31–33], knowledge systems [21,34], and inclusive wealth [35,36].

Why do we need food systems informatics? Food systems informatics addresses the underlying information deficiencies described in our introduction, which inhibit the innovation and transformation of the food system. Specifically, FSI focuses on data science innovations in engagement, information discovery, analytics, and translation to enable equitable access to better data and assessment capabilities for use by food system actors and advocates and to facilitate co-creation of innovative solutions. As highlighted in Figure 2, FSI approaches food system transformation as a set of information problems, including information needed to convene representative stakeholders and for understanding conditions, trends, and tradeoffs among key issues. FSI platforms thus play central roles in enabling the convening of stakeholders and negotiation and collaboration among them, as well as bringing relevant data to bear in the search for solutions.

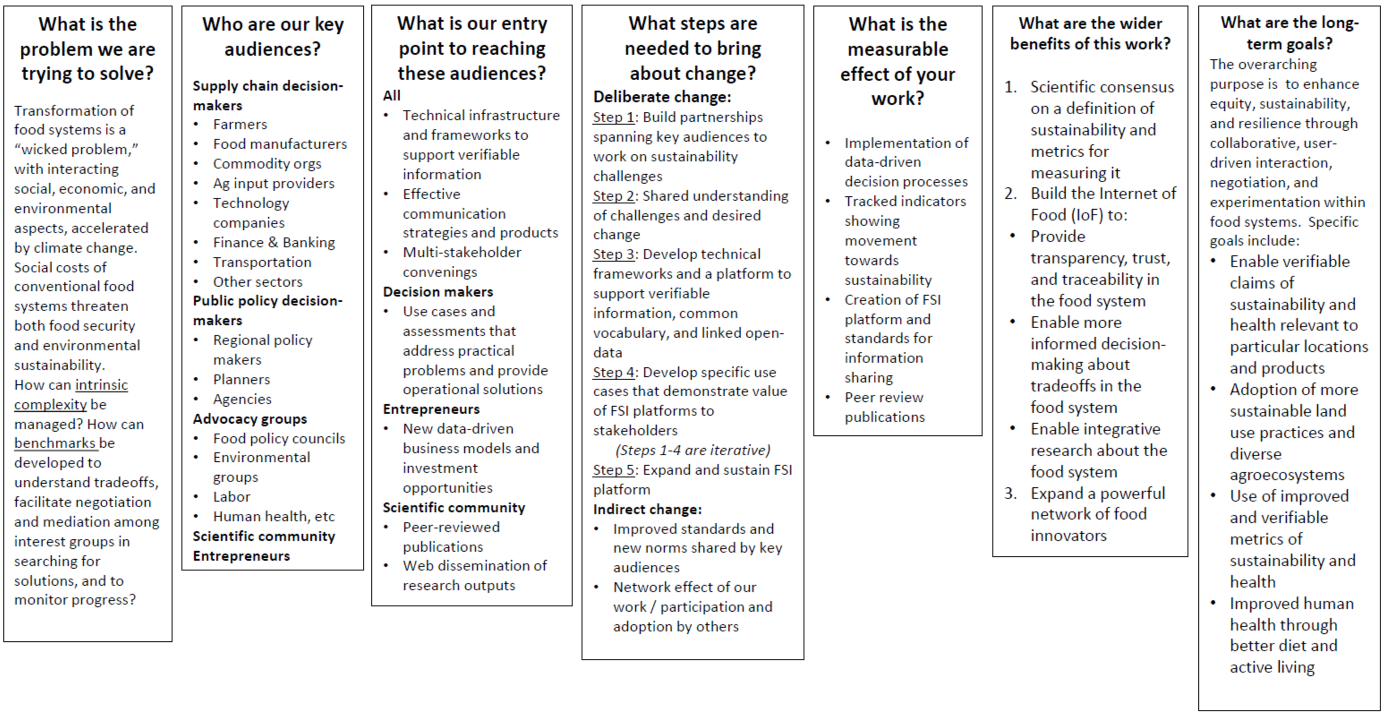

Figure 2. A theory of change for food systems transformation. Source: created by the authors.

Data science tools, products, and associated research and development questions. Relevant informatics tools include information exchange standards (e.g., ontologies, controlled vocabularies, and data schemas) and information discovery tools that allow users to apply those standards to identify existing data or knowledge on particular entities or processes, and perhaps to accurately classify unincorporated prior work, knowledge graphs derived from use cases of food system challenges and opportunities, generalized workflows, legal frameworks and data governance standards, and development of APIs (standardized machine to machine interfaces), as well as human interfaces (user interfaces/user experiences (UI/UX)). Analytical tools include descriptive, predictive, and explanatory analytical methods for networks, relationships among food system actors (e.g., social network analysis), activities, and structures. Food system structures include both patterns of organization in the many elements of the food system (e.g., facilities, transportation routes, natural resources), and more specific to FSI, the many ways in which data describing the food system is collected, stored, and used (e.g., linked open data, FAIR data, distributed ledger systems, blockchains).

Community-based use cases identify and, ideally, connect interested and affected individuals and organizations, enabling more effective partnerships and networks, data sharing, and integrated assessment of challenges and opportunities identified by and with community members. Entire communities can contribute to identifying data and knowledge gaps that need to be addressed. For example, a "food access for healthy families" use case could identify the full range and optimal combination of services available to food-insecure people, while a food supply chain use case could explore options for the reconfiguration of supply chain flows and critical infrastructure needs for providing more stable flows of food products despite disruptions, such as the labor shortages caused by COVID-19.

Development of workflows derived from use cases. There are a number of different types of workflows. A scientific workflow is the most widely-used type and has been defined narrowly by [37] as: "the description of a process for accomplishing a scientific objective, usually expressed in terms of tasks and their dependencies". Another, more generic definition we have found useful is: "A workflow consists of an orchestrated and repeatable pattern of activity, enabled by the systematic organization of resources into processes that transform materials, provide services, or process information. It can be depicted as a sequence of operations, the work of a person or group, the work of an organization of staff, or one or more simple or complex mechanisms. From a more abstract or higher-level perspective, workflow may be considered a view or representation of real work" [38]. Workflows differ in terms of context and use, for example:

- Scientific workflow: data curation in a research setting
- Business workflow: commercial processes in a private enterprise
- Policy design and implementation workflow: policy impact analysis in a public agency or an advocacy organization
- Stakeholder workflow: power analysis in political science or public administration
- Assessment workflow: negotiation support in sustainability science

An important element in the generalizability of FSI is for others to be able to replicate the assessment and analysis of similar food system issues. Generalized workflows that are built up from experience with partners can be used to accelerate the development of new use cases as needs arise in response to changing opportunities and circumstances, thereby enhancing the adaptive capacity, agility regarding shocks, and overall resilience of the food system. For example, a workflow may consist of performing a set of structured interviews of a wide range of community members with varying interests in and perspectives on a given problem or opportunity, tagging interview materials using consistent terminologies linked to existing ontologies, visualizing the linkages between stakeholders, issues, and resources, and cataloging resources present in the use case such as actors, institutions, and datasets. Cumulatively, specific use case experiences provide a platform to further develop a generalized workflow for responding to food system community needs. Other examples include workflows for annotating a corpus of documents, such as organizational websites describing relationships among stakeholders and strategic plans. Such a corpus could facilitate later research on machine learning and natural language processing for inferring these relationships from readily available documents.

Standards for integrated information exchange, including food systems ontologies, could further develop functional data resources across a number of domains ranging from food science to conservation planning. The most widely cited definition of an ontology in computer science from [39] states that "an ontology is an explicit specification of a conceptualization". An evolving operational definition we have found useful is: "In computer science and information science, an ontology encompasses a representation, formal naming, and definition of the categories, properties, and relations between the concepts, data, and entities that substantiate one, many or all domains of discourse" [40]), especially controlled vocabularies (e.g., AGROVOC https://agrovoc.fao.org/browse/agrovoc/en/ accessed on 15 March 2023) and data schemas, and open data networks (e.g., Global Open Data for Agriculture and Nutrition https://godan.info/ accessed on 15 March 2023). Building replicable tools and applications depends on development of standards at many levels, including but not limited to standards for ontology development and reuse, minimum amounts of information (data shapes), and metadata. One example application is improving the information transfer between food producers and distributors and food banks and pantries. Food producers and distributors may have excess food they cannot sell commercially but instead wish to transfer it to food banks. The exchange can be facilitated by developing a data schema describing food transfer logistics, but stakeholders should have a great deal of input into the design of the data schema to ensure that the correct fields and interrelationships are captured. Developing this data schema would provide a standard that could be used widely. Open questions remain, however, such as how to best work with communities to co-create such standards, and what tools or approaches for engagement will facilitate translation of community data needs into a formally defined exchange standard.

Ontology-based food system knowledge graphs are needed to capture and visualize the complex networks of concepts, relationships, and data across large, heterogeneous, yet convergent domains that comprise the food system. A set of modular and integrated ontologies that conform to standards and underpin food system knowledge graphs building on existing research on ontologies of food system actors, including a people, projects, organizations, and data ontology ("PPOD") [41] and an issues-and-indicators ontology of food system impacts and vulnerabilities [42,43], could be deepened and enriched with sectoral detail (for example, for food access or meat processing), linkages with related ontologies, such as health [44] and environment and resources [45], and lead to novel food systems ontologies (food systems power, policies, transformation strategies, and project implementation). Extensions of food systems thinking to the humanities—including philosophy, aesthetics, and culture—are particularly exciting in terms of the central roles of dynamic food preferences, choices, and experiences and interactions and feedbacks with values, tastes, and preferences [46,47] and likewise in documentation of "tangible and intangible aspects of a cultural object" [48], such as a recipe, a meal, or a harvest festival.

At the same time, ontologies also could enable the development of further applications, such as creating catalogs of food system actors and resources for information sharing, testing prototype AI tools for search and query, such as Natural Language Processing (NLP) systems for automatically finding and indexing food system resources, and providing a formal structure for characterizing linkages in the food system, which may help analyses such as identifying food system vulnerabilities. Yet, moving forward with building such knowledge graphs leads to a number of challenges. To begin with, are there scalable approaches for gathering information across a regional food system to create a knowledge graph that is comprehensive and yet accessible enough to be useful to the community? Second, how does one build knowledge graphs that respect privacy where needed? Is there a middle road for information sharing in knowledge graphs that falls between the full openness of the linked open data model and the inaccessibility of closed proprietary information sets?

Interoperability and access. We take it as axiomatic that it is not feasible to create a comprehensive food systems informatics platform as a top-down exercise. Activities and outputs based on these tools must be interoperable to build cumulatively across use cases and crosscutting research themes. FSI platforms will exist at both the level of cyber-infrastructure and at the level of social engagement. At the cyber level, there are three major components: data infrastructure, human interaction elements, and documentation and repositories. The data infrastructure will host knowledge graphs, tool suites, and computational engines for analytics, and machine-readable APIs for data access. Human interaction will center on websites providing front ends to the knowledge graphs, query, update, visualization, and analysis tools, and mechanisms for social interaction that support planning, negotiation of tradeoffs, policy development, and coordinated action for system change.

User interfaces that fully support a simultaneous top-down and bottom-up, community-engaged approach to food system transformation remain poorly developed for any of the necessary functions, including data contribution, query, display, curation, and analytics. Prototype UI/UX development could proceed along various lines including information about relationships between food system actors; retrieval of information and visualization tools of the network of relationships between actors; individual and shared ownership of content; web mapping tools that elucidate spatial relationships; and ultimately a collection of multiple, federated, interoperable knowledge graphs describing the food system in depth. For example, linking spatial information to semantic web databases has been an ongoing research concern (e.g., [49]), and exposing provenance information that can be stored in a knowledge graph (e.g., historical information about food processing facilities) in a web mapping interface may lead to increased user engagement. Current work on more advanced UI/UX interfaces includes democratizing access to artificial intelligence (e.g., ICICLE https://icicle.osu.edu/ accessed on 15 March 2023). Ultimately, such interfaces must achieve the aforementioned qualities of sustainable and resilient food systems: inclusion, equity, and balancing power differentials in access to data and their use to answer questions. More generally, Schuler [50] (p. 1) has argued "The primary aim of technology in the service of democracy is not merely to make it easier or more convenient but to improve *society's civic intelligence*, its ability to address the problems it faces effectively *and* equitably" (emphasis in the original).

3. FSI Applications to Enhance Sustainability, Resilience, and Equity of Regional Food Systems

The emerging FSI field is envisioned as the information platform for "smart and connected" regional food systems. By using "smart and connected" here and in the title of this collection, we mean the application of data science tools to address the information failures highlighted in our theory of change for food systems transformation (Figure 2). The rationale for a regional focus draws on [32,33,36,51,52] on physical and social infrastructure necessary to provision major cities and how these investments and differential capabilities affect inequalities of outcomes in the US.

Our approach to convergent research and negotiation support at the regional scale is iterative and embraces two interacting opportunities for collaborative community engagement:

Generalized application 1: Engagement and inclusion for participation and partnership across the food system: engaged, inclusive, and diverse participation to build the social capital necessary for co-creation of solutions, including building necessary networks and partnerships for data access, sharing, and analysis.

Generalized application 2: User-driven research on food system problems and opportunities, including collaborative development of ontologies, indicators, data analytics, and model technology needed to co-create and act on data-informed experimentation, while leveraging indicators and measures of progress to influence change.

These two interlinked applications share a number of important attributes. Each is an important aspect of *a food system as both a set of human relationships* and *as a set of activities* including the impacts and vulnerabilities associated with those activities [14]. Each has at its core an information problem; in other words, better data and information is a necessary (but not sufficient) condition for better outcomes in terms of equity, prosperity, sustainability, and resilience. These collaborative opportunities are mutually dependent: prospects for better outcomes depend on parallel and articulated work on both human engagement and the assessment of activities, impacts, and vulnerabilities.

Assessment workflows combine scientific and stakeholder workflows. To accommodate the duality of food systems described above—as both systems of human relationships and of activities for the production, processing, marketing, and consumption of food—we introduce here the concept of "assessment workflows" (Figure 2), which combines familiar notions of scientific workflows (discussed in Section 2 above) with "stakeholder workflows". The workflows summarized in Figure 3 were derived from our experience with participatory development of specific use cases, with particular reference to several reported in this special collection, in which engagement with diverse food system stakeholders was the basis for (and interacted with) scientific activities in support of those efforts. This responds directly to calls for a new "knowledge–policy interface" for the food system [9] and not just another "science–policy interface" [53].

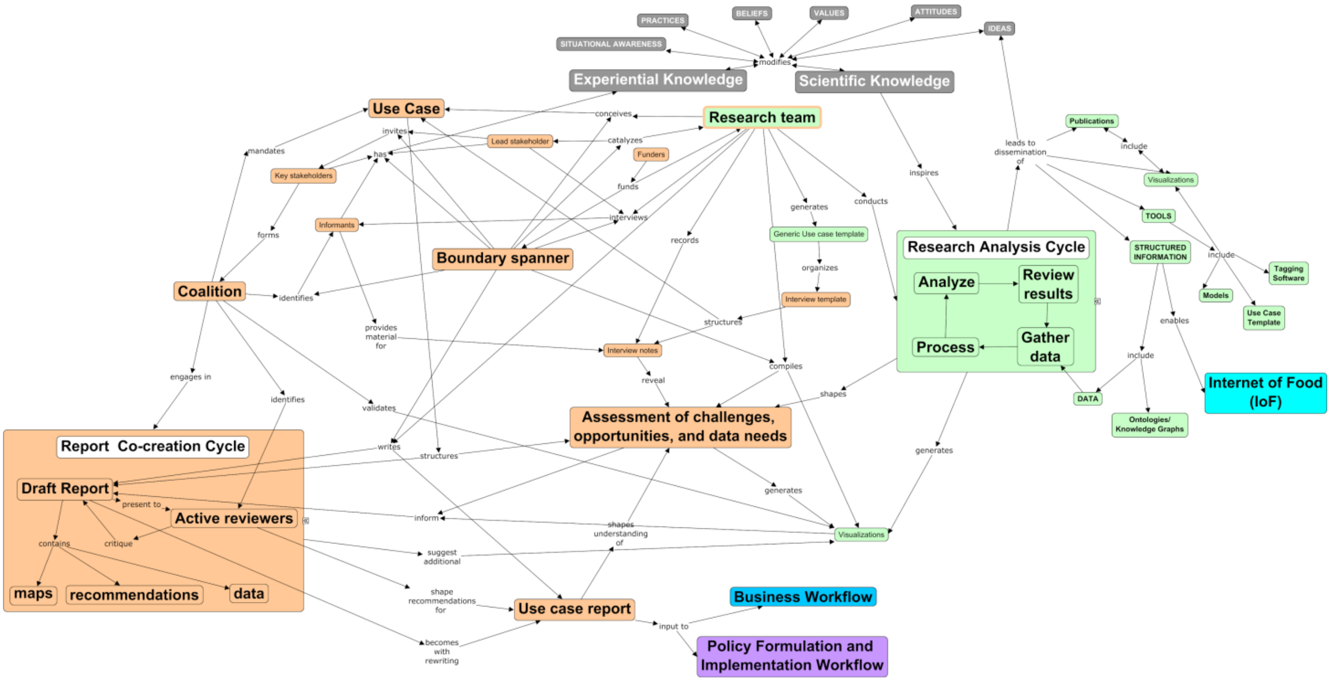

Figure 3. Assessment workflows combine scientific and stakeholder workflows. Source: created by the authors based on experience collaborating with numerous stakeholders.

Of necessity, Figure 3 is a simplification of these complex processes. In particular, since the concept already will be familiar to many, the schematic depiction of scientific workflows in Figure 3 is highly streamlined into "research analysis cycle" activities (indicated in green in Figure 3). Based on the authors' experiences with the development of use cases, a bit more detail on the greater process is elaborated for the "stakeholder workflow" activities (indicated in peach color in Figure 3). Of course, each application will differ in its details, but there are some common elements. For example, reflecting best practices in integrated ecosystem assessments [54], a mandate from a coalition of stakeholders initiates the assessment workflow and parallel development and interaction of the scientific and stakeholder activities. This is rooted in theories of policy processes [55] and particularly "advocacy coalition theory" [56]. Thus, rather than the curiosity-inspired impetus typical of a detached, scientific workflow, the impetus for an assessment workflow arises from a mandate from a specific advocacy coalition. Note also the central role for a dedicated "boundary spanner" [20], who facilitates communication and interaction between the stakeholders and scientists contributing to the overall process. In turn, as shown in Figure 3, this process creates the groundwork both for business workflows and policy formulation and implementation workflows, while also extending ontologies and instantiating knowledge graphs that contribute to the development of the Internet of Food. While this generic workflow is presented for heuristic purposes, a more realistic depiction of the creation of an actual use case likely would be presented as a series of adaptive management cycles, revisited over an extended period spanning many months, if not years. In the same vein, reports and other documentation are provisional, rather than "final", informing further engagement, action by private sector businesses, public sector agencies, and civil society, and knowledge creation that is readily accessible and widely useful across sectors.

Stakeholder-driven use cases. User-defined use cases have been important vehicles to pursue the two interlinked collaborative opportunities described above. They have guided the development of digital technology that can harness and generate social capital for prioritizing issues, indicators, data, data sharing, ontologies, management strategies, and co-created pilot projects aimed at systemic solutions through socio-technological convergence. We can characterize the contributions to this special collection as a set of use cases, which typically have been specified and prioritized by a set of community partners to address key food system challenges in a network-of-networks approach (Figure 1).

Using rapidly expanding linked open data resources and the burgeoning Semantic Web of Food (SWoF) within the Internet of Food (IoF), we believe it will be possible to connect and facilitate the use of fragmented and hidden data by social actors at multiple scales. The next step is creating a food system knowledge graph (KG) on easy-to-use, pluggable platforms capable of integrating and "cross-walking" (also called "ontology negotiation") existing ontologies and datasets, thereby facilitating open access to extensive food system knowledge stores. Innovative IP and privacy standards must be co-created in tandem to assure equitable outcomes. Real-time connectivity and sharing of data will help enable networks of innovators who currently work in isolation and drive innovation in agricultural practices, food products, and social institutions based on social and environmental effects that largely are omitted in current market prices. Ultimately, the process will accelerate as community social actors share and learn from each other, scaling and replicating sustainable, resilient, and just food systems in their communities.

FSI use case examples. The following examples illustrate a range of use cases that are in development, or which could be developed as modular components of FSI platforms (see Figure 1).

(A) Food supply chain diversification. Almost everywhere in the US, critical processing infrastructure is missing that, if created, would result in system-wide shifts (spanning production, processing, distribution, and consumption) that would contribute to inclusive economic development in both rural and urban areas while increasing food system resilience in the face of disruptive events, such as the COVID-19 pandemic [25,57,58]. One entry point for this work has been meat processing supply chains that were disrupted as a result of COVID-19, and which are highly concentrated at processing stages [59]. Ongoing work has broadened to encompass regional supply chains. Examples of successful outcomes include knowledge graphs with appropriate intellectual property protections to match producers, processors, distributors, and consumers and bypass chokepoints caused by over-concentration or poor awareness of alternative options. Indeed, successful outcomes may be less knowledge graphs *per se* than the unleashing of knowledge-graph connections to enable commercial transactions and ameliorate food inequities.

(B) Food access for hungry people. Currently, access to available food security services falls far below need because the services are poorly communicated and coordinated, such that conventional targeting omits specific needy consumer groups and disadvantaged populations within particular neighborhoods. An initial focus to better serve omitted populations pivots on existing food preparation infrastructure (schools, restaurants, hospitals, religious institutions, food banks, etc.), which can help planners and other food system actors to address hunger emergencies. Consider one example of a successful outcome: a publicly available knowledge graph for each region that links information on food production, processing capabilities (especially in public and non-profit institutions), and marginalized groups without sufficient access to healthy, affordable food, as well as philanthropists and programs seeking to underwrite food access.

(C) Food for better health. Combining dietary prescriptions with existing in-patient nutritional and pharmaceutical options significantly improves health outcomes for underserved populations [60,61]. We anticipate that linking prescriptive diets and health information systems to food provider information systems will increase the likelihood for providers to offer dietary treatment, whilst also increasing consumer acceptance and adherence to the prescriptions. Example of successful outcomes: knowledge graphs with appropriate privacy protections to match patient nutritional needs with local sources of food.

(D) Working landscapes for regional resilience. Stakeholders' efforts are hampered by administrative "siloing" of data and information, which inhibits identification, assessment, and action to better manage critical resources and food system tradeoffs within the specific contexts of each of these contrasting agroecosystems [54,62,63]; see also [64] for a useful comparative case in an international context. In Columbus, Ohio, both farmer-led collaborators and urban planners behind the Local Food Action Plan hypothesize that solutions to local shortages and access deficiencies are feasible from such shifts in production within the region, resulting in more of what is needed, particularly fresh crop and livestock products, being produced and delivered within the region, and that such shifts will also improve economic outcomes. In California, Huber et al. [27] address regional vulnerability and options to increase resilience in the face of fire, drought, and flood risks and other likely climate and environmental shocks through better-informed regional planning processes, including planning and public investments in critical infrastructure. The work builds on previous assessments of the region's natural resource and public health characteristics conducted by the team [65–67]. Examples of successful outcomes: a publicly available knowledge graph for each region that links information on a wide range of natural resource and environmental issues, including ecosystem services, climate change mitigation and adaptation, and tools enabling new connections between suppliers and consuming organizations.

(E) Food system governance. Power dynamics are an expected feature of coupled social–ecological systems as comprehensive and complex as the food system. Power differentials and imbalances, along with varied priorities, values and interests, contribute substantially to the classification of food system issues as wicked problems. Classifying and relating the nature of these power dynamics on the social side of food systems resulted in a power ontology that has extended the PPOD ontology that had been developed earlier as a joint effort of a wide range of food system actors. Hyder et al. [28] provide an example of the potential for engagement and inclusion through a generalized application of FSI.

Challenges of scale, scope, and system boundaries. Food systems are embedded within an environment characterized by other systems, each of which interacts to drive the dynamics of the whole. Drivers and disruptors arising outside the food and agriculture system, therefore, are both expected and difficult to incorporate within FSI. Regardless, these linkages among systems become a strong element of our rationale for a convergence approach harnessing informatics to enhance effectiveness in participation, inclusion, and stakeholder engagement. As Helfgott [51] argues persuasively: "rigorous framing of resilience necessarily involves participatory systemic boundary critique and both theoretical and methodological pluralism." Building on this, we feel systematic, intentional stakeholder engagement is the most promising method for tackling the challenges of scope and scale for a specific food system and in determining workable system boundaries that have practical significance (see also [54]).

4. Discussion: Potential Outcomes and Impacts of Creating Food Systems Informatics Platforms

Vision for the future. FSI platforms hold promise to enable the co-creation of transformative changes in food systems and their associated agroecosystems. FSI building blocks for transformation paths to greater food system sustainability and resilience include replicable prototypes of food system knowledge graphs spanning many communities, enabling a holistic, inclusive treatment of the food system; appropriate, workable balance between openness and privacy in knowledge graphs, encouraging decentralized information nodes, an important step towards data democratization; and diversity, equity, and inclusion increases as foodshed distribution patterns serve a wider range of producers, processors, and consumers, creating greater economic opportunities and enabling consumers to attain healthier diets. With these FSI tools, communities could develop new mechanisms that support a combination of food access, health prescription, supply chain regionalization, and planning; in turn, these enable overall improvements in human wellbeing through preventive health measures and dietary improvements integrated within healthcare systems, particularly for populations that formerly experienced poor access to both food and healthcare. In parallel, policy coalitions spanning the food system can actively use information technology to engage and empower crosscutting stakeholder interests in food access, food for health, food supply chain business opportunities, and ecosystems services provided by working landscapes. Enabled by FSI tools, powerful networks can emerge of food system innovators, entrepreneurs, advocates, and leaders in the public, private, and non-profit sectors.

Ultimately, successful development of FSI platforms is envisioned to provide supporting cyberinfrastructure for improved resilience, sustainability, and equity of food systems. These broader impacts can be measured through tracking key system vulnerability indicators, and direct impacts through tracking uptake indicators; each of these indicators can be integral to an FSI platform. Expected direct, practical impacts include: (1) Creation of a rigorous, data-informed consensus on scope, benchmarks, and practical tradeoffs regarding inclusion, sustainability, and resilience in food systems that can be applied anywhere (rather than reinventing); (2) Institutional and legal innovations to enhance intellectual property and incentivize innovation; (3) Expansion, interlinkage, and empowerment of networks of food system innovators and entrepreneurs; (4) Entrepreneurs and innovators capturing value by advancing equity, sustainability, and resilience; (5) Farmers, ranchers, and processors branding products and services that add value through enhanced inclusion, sustainability, and resilience; (6) Data science tools that streamline and reduce costs of compliance for food safety, labor regulations, and environmental standards; and, as discussed below, (7) FSI ontologies and information-discovery tools built upon them that can enable more effective and evidence-based negotiations among food system actors, and (8) enhancing local producers' and processors' markets and incomes, for example, by enabling supply chain alternatives to concentrated and lowest-common-denominator systems controlled by a few huge companies.

Each of the FSI use cases discussed in Section 3 above exemplifies user-driven transdisciplinary research. Either engagement without analysis or analysis without engagement perpetuates the disappointing "state of the art" summarized in Table 1. In particular, expert-driven analysis without engagement is a formula for irrelevant or even harmful misguided top-down actions. Thus, while each of the collaborative opportunities described above is independently poised for an "information revolution", transformational advances depend crucially on an integrated approach, as mapped in the assessment workflows depicted in Figure 3, and a corresponding vision for the practical implications of FSI innovations is sketched in Table 1, which was developed by the co-authors. Thus, FSI platforms provide novel means to overcome barriers to well-informed collective action.

Table 1. Vision for innovations enabled by food systems informatics. Source: created by the authors.

Collaborative Opportunity	State of the Art	Vision for Game Changing Innovations
Engagement and inclusion for participation and partnership across the food system	Static "Rolodex" of established contacts; tends to involve the same familiar cast of characters. Tools: Personal networks and electronic contact lists based on past interactions and chance encounters. Pitfalls: Marginalized groups remain invisible or are engaged haphazardly. Important voices are omitted from assessment, creation, and implementation of "solutions". Temporally dynamic engagement in collaborations is not accounted for. Interventions are misguided or unusable. Inequities and injustices are reproduced. Innovation is constrained and creative opportunities are missed.	**Dynamic social network analysis opens avenues for active partnership, data discovery and access, and discovery by key stakeholders**. **Tools**: People, Programs, Organizations, Data (PPOD) ontologies of diverse food system actors and resources; knowledge graphs enhancing purposeful social networking for each region. **Advances**: intersectional data on complex, multidimensional identities of people, programs, organizations, and data enables fresh, focused, and effective inclusion and data-informed interaction. The clearing house includes more diverse people and incubates more creative ideas. Participants can discover partners whom they otherwise would not meet at all. Shifting composition of collaborative groups can be accommodated without losing opportunities to engage and re-engage partners over time.
User-driven research on food system problems and opportunities	*Ad hoc* workshops with little access to data that does exist and limited capacity to fill data gaps. More holistic, data-informed assessments are prohibitively time consuming and rapidly obsolete. Tools: "sticky notes", flip charts for visual recording, logic models and conceptual maps. Pitfalls: Repeated "reinventing of the wheel" with little or no cumulative understanding of dynamic, complex problems. Keyhole vision focuses too narrowly and misses both threats and opportunities. Time bounded "seat of the pants" brainstorming with little opportunity to test consistency of assumptions or to consider more than one (or a few) issues or approaches at a time. Expert-driven processes squelch community innovation and creativity. Missed opportunities, rigid strategies, failure to learn from experience (positive and negative) slows progress and leads to repeated costly mistakes.	**Computer science and information technology is harnessed to break down data silos, open up public access to information, inspire data sharing, and facilitate curation to ensure data quality and fill data gaps**. **Tools**: use cases and workflows to pivot assessment activities in response to shocks and other changes in circumstances; relational, system, and meta ontologies for linked, open food system data flows; knowledge graphs to supply data for relevant scales within spatial context and (increasingly) in real time. **Advances**: more holistic, community-driven, data-informed assessment of problems and opportunities becomes feasible because time and effort required to pose questions and seek answers is dramatically reduced. Clearing house links concerns and insights from community experience with analytical capabilities and curated, contextual, timely data. Scientific foundations set for authentic co-creation and implementation of transformative solutions employing state of the art tools, for example visualization, scenarios, and foresight; real time "dashboards" to benchmark progress.

5. Conclusions and Policy Implications

Building on over a decade of work, including five years of implementation of an NSF-funded Research Coordination Network on "Smart and Connected Regional Food Systems", we have introduced food systems informatics (FSI) as a tool to enhance equity, sustainability, and resilience of food systems through collaborative, user-driven interaction, negotiation, experimentation, and innovation within food systems. Specific benefits we foresee in further development of FSI platforms include:

- Capacity to create verifiable claims of sustainability, food safety, and human health benefits relevant to particular locations and products.
- Better incentives for the adoption of more sustainable land use practices and for the creation and stewardship of more diverse agro-ecosystems.
- Widespread adoption and practical use of improved and verifiable metrics of sustainability, resilience, and health benefits arising from practices affecting how our food is produced, processed, marketed, and consumed.
- Overall, improved human health through better diets.

Together, these FSI tools and platforms promise to be highly relevant in efforts to address major food policy challenges by policymakers, food system advocates, and private enterprises, including farmers and processors. In particular, they offer important tools for the development and curation of quantitative benchmarks to understand tradeoffs across policy objectives and facilitate negotiation, mediation, and innovation across stakeholder groups (often with conflicting perspectives, beliefs, and interests) in collaborative efforts to search for solutions and to monitor progress that drives improvement, further refinement, and innovation. In addition to further technological developments and significant effort to create informatics tools and to instantiate knowledge graphs, priorities for further steps to realize this vision include the following investments and innovations.

Investment to build social capital. Socio-technological investment is key to overcoming barriers to effective collaboration on food system challenges and opportunities. Co-creation of solutions to these wicked problems that are feasible technically, economically, socially, and politically requires investment in social capital. The social networking and informatics tools that have been developed [41] can dramatically improve efficiency (lowering search, transaction, and negotiation costs) and effectiveness in spanning boundaries to co-create innovative solutions [20,41]. Together with partners, we have designed ontological underpinnings for a Semantic Web of Food (SWoF) [68,69] that lay the knowledgebase foundation for a connected Smart Food Shed.

Community engagement, diversity, and inclusion. Democratization of food system data through open access is necessary so that communities can share information and inspirational solutions and advocate for data-informed policies and programs supporting sustainable, resilient food systems and healthy communities. Ultimately, our vision is to link and expand a powerful, inclusive network of advocates, innovators, and entrepreneurs, creating local innovations shared through global networks for practical action for food system sustainability, resilience, and justice, buttressed by validated metrics. Food system challenges disproportionately affect vulnerable communities within each region; however, novel, practical solutions often come from community-level innovators to co-create and scale out practices, tools, and strategies to enhance food system sustainability, resilience, and justice. This also carries an obligation to indigenous peoples and other marginalized groups to "ensure that due recognition, acceptance, and prominence are given to traditional knowledge" [70].

Local innovation and entrepreneurship. Resilience, particularly adaptive capacity in the face of unknown and unpredictable challenges (COVID-19 being a current example, but climate change also providing many others), requires diversity across many dimensions of food systems as the building blocks of adaptation. How can programs of engagement and convergent research best support the co-creation of resilient and entrepreneurial agricultural and business ecosystems that can readily respond and adapt to food system challenges? Our hypothesis is that social and cultural diversity and inclusion spur food system innovation and entrepreneurship. Our ongoing work includes a design of means of combining diversity in multiple forms, including inclusive community engagement, with technological advances in data science to address the issues of concern in our communities by connecting these diverse voices with relevant, but currently disconnected, data [41]. Further socio-technological innovations are needed to support self-organizing social and economic activities in diverse agricultural ecosystems, working landscapes, and inclusive food systems. We further hypothesize that convergent research can best provide concrete benchmarks to measure progress and understand tradeoffs among strategies along multiple dimensions, and thereby spur the transformation to smart foodsheds with greater resilience and enhanced human wellbeing [63,67].

Transparency. Innovative IP and privacy standards must be co-created in tandem to assure equitable outcomes. Real-time connectivity and sharing of data will create a network of innovators who currently work in isolation and also drive innovation in agricultural practices, food products, and social institutions based on social and environmental effects that largely are omitted in current market prices. Creation of a Semantic Web of Food (SWoF) is the entry point for this complex opportunity to connect open data streams and co-create useful knowledge graphs in response to pressing needs across our complex food systems. Ultimately, the process will accelerate as community social actors share and learn from each other, scaling and replicating sustainable, resilient, and just food systems in their communities.

Data democratization. We believe that open access to information, tools, and other technical infrastructure can lead to the democratization of knowledge. This requires embedded mechanisms for transparency, inclusiveness, engagement, collaboration, and data-informed community co-creation. "Crowdsourcing" is one superficial term for this, although more radical is the idea of open validation; this process determines whether the problems identified and solutions co-created are viewed as legitimate (in the sense of a fair and open process) by the communities concerned. FSI tools—generalized workflows, ontologies, knowledge graphs, and ultimately community-identified and creatively generated solutions—highlight the need for decentralized data curation and maintenance, since we hypothesize that they enable a more transparent, accountable, and, hence, democratic food system. Specific questions in these new lines of FSI research and development include how to strike an effective balance between centralized and federated information architectures when dealing with the complexity and dynamics of food systems. Perhaps different information architectures suit different use cases? How does a community-based, user-driven approach affect the answers to these questions?

The ontologies underpinning the Semantic Web of Food link could also make data more FAIR (Findable, Accessible, Interoperable, Reusable) through the integration of labor, environmental, governance, and other concerns at the heart of inclusive growth. "Data democratization" underpins this work, which means FAIR data access while respecting individual data privacy. Co-creation of practical IP and privacy standards and shared data ethics norms are prerequisites to data democratization. Current institutional weaknesses undermine incentives for innovation and entrepreneurship and disadvantage those outside mainstream food supply chains. Antidotes include shared best practices for environmental-social-governance (ESG) reporting and the exchange of data, support for co-creation of informatics tools, and interfaces based on innovative metadata standards. This will reduce costs of collaboration, helping to level the accountability "playing field" underpinning traceability, transparency, and (ultimately) trust. In turn, these are essential to data-informed advocacy and collective action by social actors to create sustainable, resilient food systems and healthier communities. Complementary to FAIR data are the CARE principles (Collective benefit, Authority to control, Responsibility, Ethics). Originating in discussion around Indigenous data sovereignty, the CARE perspective emphasizes governance of data for the collective benefit of marginalized communities [71]. The CARE principles might resonate with many communities in the food system.

Distributed infrastructure for data and analytics. A further necessary requirement for these advances is to explore how legal and institutional safeguards for privacy and intellectual property (and other civil and human rights) also are necessary to spark the local and regional creativity, innovation, and entrepreneurship needed for transformation of the food system. We believe that moving towards decentralized data infrastructures is important for democratization of systems, especially including food systems. However, it is not clear what sort of social or technological mechanisms will lead to a move towards decentralization. We need to identify and assess specific classes of information, such as geographically localized materials and cultural practices, that lend themselves most naturally to be deployed through a decentralized infrastructure. Furthermore, data democratization requires attention to the social and political economy in which the food system informatics infrastructure is maintained and developed. It is not sufficient merely to open standards for food systems informatics protocols. One needs funding for actual hardware and systems administrators to run it and maintain it. This is by no means assured; possible models for the funding and organization of data infrastructure range across extremes from globalized "surveillance capitalism" [72] to extremely decentralized cooperative economies. At the same time, one must recognize that decentralization poses challenges for authentication, privacy, and ease of use, among other issues. Legal expertise is essential to provide specific recommendations and policy insights for multiple aspects, including transparency, data protection, licensing, data ownership, data sharing, cyberlaw, and other relevant intellectual property issues.

Caveats. The digitization of food systems and study of food systems informatics introduces risks, as well as social and economic benefits. Resolving issues of inclusion in problem definition and the creation of solutions, equity of outcomes and access, data privacy, intellectual property, and managing political and economic power differentials are essential for desirable (indeed, essential) advances toward food system sustainability, resilience, equity, and justice, including data democratization. Yet, patent trolling, perversely designed licensing and privacy agreements, greenwashing, and disinformation campaigns each hold potential to exacerbate information, access, and ownership asymmetries and thereby to concentrate wealth and power. Knowledge is power—and digital technologies carry risks of increasing power elites' capabilities to gather and hoard knowledge in order to hold onto and enhance their power. Digital technologies also hold potential to lay bare food system "attack surfaces" to bad actors. Therefore, looking forward, food systems informatics also must expand its scope to include food systems security, privacy, and intellectual property considerations within its disciplinary purview. In turn, food systems security itself will necessarily and increasingly include food systems cybersecurity in an ever more digital world.

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