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Modeling Sustainable Agriculture

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Modeling Sustainable Agriculture

DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Software Engineering

by

Ankita Raturi

Dissertation Committee:
Professor William Tomlinson, Co-chair
Professor Debra Richardson, Co-chair
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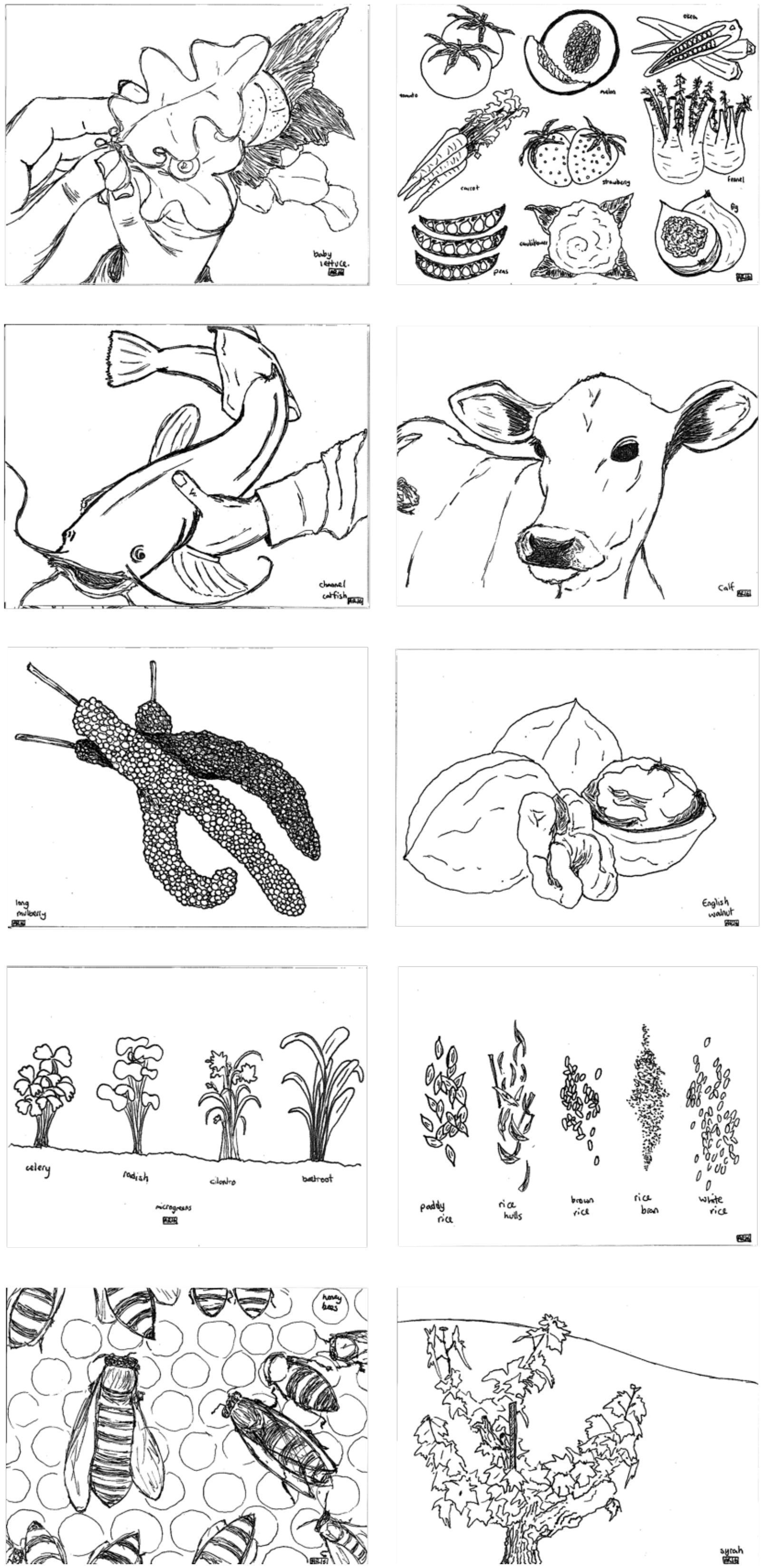

Illustrations of agricultural plants and animals. *From top, left to right:* Baby lettuce, assorted fruits and vegetables, Channel catfish, Jersey calf, Long mulberries, English walnut, assorted microgreens, rice at various stages of processing, Honey bees, Sryah grapevine.

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ABSTRACT OF THE DISSERTATION

Modeling Sustainable Agriculture

By

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Doctor of Philosophy in Software Engineering

University of California, Irvine, 2017

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Agriculture is a critical component of the human food system. Its coupling to the success of human societies and its impact on the environment is nontrivial. Varied efforts — including new regulations, certifications, techniques and software — exist to assess and improve the sustainability of agriculture. Multiple stakeholders in a fragmented field, with tensions and pulls in different directions, results in a duplication of efforts and disconnected data and processes.

To explore the challenges that exist in modeling sustainable agriculture, I characterize environmental assessment as a modeling process, and secondly, characterize sustainable agricultural systems as a type of complex adaptive system. Framing the assessment process and system of interest in this manner permits the application of various techniques from software engineering, systems analysis, and human-computer interaction to tease apart the core issues and to subsequently respond to these challenges through design.

First, I present an analysis of the capacity of Life Cycle Assessment (a formal and quantitative environmental assessment technique) to represent small- to medium-scale sustainability-oriented farms. Then, I described a qualitative field study, in which I visited 16 farms across California, interviewing sustainability-oriented farmers, and collecting samples of farm data.

The goal of this study was to uncover how and why farmers model farms in practice, the nature and availability of farm data, and the experiences of farmers with various environmental assessment techniques.

The findings of these two studies resulted in the articulation of domain-specific modeling requirements. These include: creating selective and partial system models, knitting together qualitative and quantitative data in system models, capturing both spatial and temporal structures, and all of this through models that are abstract yet grounded in real farm data.

Building on these studies, I present MoSS: a framework to enable the Modeling of Sustainable Systems. MoSS consists of three parts: an abstract model, domain-specific elements to allow for modeling agricultural systems, and model 'perspectives' that allow for the assessment of the environmental performance of the system. I conducted a scenario-based evaluation of MoSS to assess its ability to express the varying dynamism and complexity of sustainable agricultural systems. MoSS addresses the core challenges involved in modeling sustainable agriculture, providing a consistent mechanism to capture the essence of farms.

MoSS represents a step forward in grounded information design for sustainable agriculture, paving the way for the design of information management and environmental assessment tools that more closely meet the needs of small- to medium-scale farms and farmers. Through the work presented in this dissertation, I have also demonstrated how one may engage in applied and interdisciplinary software engineering research to support sustainable development.

Chapter 1

Introduction

Food is essential; its infrastructure, complex. Agricultural systems are a critical component of this infrastructure, providing crucial food products as part of the human food system, but also providing vital agricultural by-products as inputs for other industrial systems [158]. They are deeply coupled with the natural environment and undergird human civilization [110]. The resulting impact of our food production activities on the environment is profound [110, 102].

As this web of systems — industrial, agricultural, environmental, human — grows more intricate, it becomes increasingly difficult to understand and map out the consequences of our actions. Agricultural systems are, thereby, commonly assessed to improve economic performance, reduce environmental impacts, and improve social sustainability [110, 202].

System assessment begins with the representation of a system through some modeling process, and a subsequent evaluation of the model with respect to certain attributes. This process involves the collection, structuring, manipulation, and storage of a variety of data. System assessment often involves multiple modeling processes as each model is created to represent a particular aspect of a system and its performance. While instrumental in improving our understanding of these complex systems, these efforts have led to a fragmented field with tensions and pulls in different directions, and have resulted in a duplication of effort, and moreover, data and processes that are disconnected.

Over the past decade, small- to medium-scale sustainable farms (e.g., urban farms, organic farms) have been growing in popularity [233]. There is an increasing demand for food that is grown sustainably, raised humanely, and produced with fair and just labor practices [202]. This has spawned many efforts to curtail environmental impacts: including, numerous regulations, eco-labels, and certifications [203, 57, 129]. Such efforts often require farmers to engage in additional record keeping that can be both tedious and time consuming. Farmers, in essence, pay for the privilege of growing food sustainably.

Despite growth in this sector, there is a lack of appropriate technological tools, arising in part from a mismatch between existing tools — which are typically designed for large-scale industrialized agricultural practices — and the needs of farmers who work at smaller scales. With this comes a growing need for systemic mechanisms to understand, analyze, manage, and further improve, sustainable agricultural systems.

There is no dearth of analyses of the environmental impacts of our food systems, but there is a lack of connectivity across the plethora of models created and a lag with the changing real world that is represented.

In this dissertation, I explore the landscape of environmental assessment in sustainable agriculture, seeking to understand farm stakeholder requirements and challenges, and subsequently design solutions to meet their needs. The motivating research questions for this dissertation are as follows:

1. How are agricultural systems modeled when the goal is to assess their environmental performance?

2. How do small- to medium-scale, sustainable farmers model their agricultural systems to assess environmental performance?
3. What are opportunities for design to address the hypothesized mismatch between formal modeling methods and farmer modeling practices?
4. Do the designed artifacts (resulting from R3), adequately address the modeling challenges faced by small- to medium-scale farmers (identified through R1 and R2)?
5. What are the broader implications of this work for design and modeling research in the domains of sustainability and agriculture?

These questions are contextualized in Chapter 2 and tackled in each of Chapters 3 through 6 of this dissertation, culminating in a discussion of broader implications in Chapter 7. A summary of the contributions of this dissertation is available in Chapter 7.

1.1 Motivating Example: An Urban Farm in California

Agricultural systems are composed of heterogeneous subsystems with varied environmental impacts. For example, Figure 1.1 shows Alegria Fresh Farms, an urban farm in Orange County, California [8].

It is a small-scale farm that produces fruits, vegetables and a variety of agricultural by-products such as organic soil. It is not a single product system. A number of subsystems are present within the farm for irrigation, solar energy production, hydroponic cultivation, hydroponic vertical cultivation, certified organic cultivation, vermicomposting, and a nursery, among others.

To understand which subsystems are more responsible for certain environmental impacts, one would need to be able to attribute impacts to particular subsystems and processes.

Figure 1.1: Alegria Fresh Farms [9].

This would show the farmer which cultivation method, for example, is more environmentally friendly.

The hydroponic vertical cultivation subsystem shown in Figure 1.2 exemplifies the complexity of modern agriculture, even at this small scale. Many of the materials described are sourced externally from other industrial systems. Many external data are therefore required to accurately assess the environmental impact of the farm. Availability and access to the environmental impact data of these external components is not guaranteed.

Agricultural systems are also constantly evolving: equipment is upgraded, cultivation methods are refined to optimize certain metrics (water use, product output, fertilizer requirements etc.), subsystems grow and shrink, and food types grown change according to supply and demand, in addition to season.

Figure 1.3 shows two satellite images of Alegria Fresh Farms: the image on the left is the farm shortly after it was set up. Alegria Fresh Farms was one of a set of small experimental

Figure 1.2: Hydroponic vertical setup: "EnviroIngenuity Custom Vertical Garden tower with 8 pots and a custom base" [8].

and demonstration farms that were introduced to the Orange County Great Park in around 2009 [88]. The image on the right was taken after several years of farm activity [89]. The farm has since been relocated.

As changes are made in an agricultural system, any models that were initially created become outdated. When models are constructed for agricultural systems, they are a static representation of a dynamic system. Once data have been collected and things change, the model is no longer an accurate representation of the system. Over the last six years, the Alegria Fresh Farms has grown, systems have changed, and as a result, the relationship of the farm with the environment has been affected. However, many models, from satellite images to layout diagrams, cannot necessarily capture the change in the system and its en-

Figure 1.3: Satellite images of Alegria Fresh Farms. Left: Recently after construction, Satellite image circa 2009 [88], Right: Satellite image, circa 2015 [89].

vironmental impacts. While there are many techniques that allow for detailed analyses of an agricultural system's environmental performance, they are primarily expert-driven technique, which means that once a model is created, it is difficult for the farmer to maintain or update it for continued use.

1.2 Dissertation Overview

Chapter 1, Introduction: In Chapter 1, I introduce the problem of interest for this dissertation and illustrate the core challenges through a motivating example.

Chapter 2, Background: In Chapter 2, I describe related work in the domain of agricultural modeling, design in the domain of sustainable agriculture, and the socio-political context of sustainable agriculture in California. These are intended to provide a high level overview of work at the intersection of agriculture, sustainability, and technology. Section 2.2 outlines the theoretical framing of this dissertation.

Chapter 3, Formal Modeling in Agriculture: Chapter 3 is a depth-first exploration of Life Cycle Assessment (LCA), a formal modeling technique commonly used to quantify the environmental performance of production systems. After selecting a geographically diverse set of LCA studies that span across food types, I investigate how agricultural systems are compared and connected using LCA, identify issues that arise in the process, and explore how models of the environmental impacts of agricultural systems are kept up-to-date.

Chapter 4, Information Management in Sustainable Agriculture: In Chapter 4, I present a breadth-first exploration of the spectrum of sustainable agriculture. The work presented in this chapter is scoped to a specific state (California) in a single country (the United States of America), on a single planet (Earth), as agriculture across geographic regions is subject to local environmental nuances, geopolitical constraints, and cultural variances. Scoping the study to California, nevertheless, allows for a preliminary exploration of a broad variety of agricultural system types. I conducted a qualitative field study involving the interview of 16 farmers in-situ, to uncover how and why they model their farms in practice, the nature and availability of farm data, and the experiences of farmers with the range of environmental assessments (both formal and informal) available. The data collected during this study was analyzed to articulate a set of challenges and restrictions faced by farmers, as well as a set of lessons to inform future design work.

Chapter 5, Modeling Sustainable Systems (MoSS): In response to the findings detailed in Chapters 3 and 4, Chapter 5 introduces **MoSS**, a framework for **Mo**deling **S**ustainable **S**ystems. In this chapter, I first describe the process of building and refining MoSS. This includes the introduction of two design methods developed as part of my broader dissertation research. The crux of this chapter is the specification of the MoSS framework's abstract model and domain-specific elements to enable the system modeling, and MoSS *perspectives* to enable model checking.

Chapter 6, Evaluating MoSS in Sustainable Agriculture: The resultant MoSS framework is evaluated through a scenario-based evaluation in Chapter 6. Here, I walk through a set of scenarios reminiscent of the types of activities conducted by previously interviewed farmers (Chapter 4) to test the MoSS framework's capacity to express the spectrum of sustainability in agriculture and the modeling challenges posed by small- to medium-scale sustainable agricultural systems.

Chapter 7, Reflections: Finally, in Chapter 7, I reflect on what it means to model sustainable agricultural systems. I highlight the contributions of this dissertation, and discuss broader challenges, and implications for design. This includes a brief glimpse into future work to realize the MoSS framework as part of a future toolkit for small- to medium-scale sustainability-oriented farmers.

Chapter 2

Background

Modeling sustainable agriculture is interdisciplinary challenge. This dissertation intersects three primary domains: systems modeling, sustainable agriculture, and software engineering. As I set out to explore challenges in modeling sustainable agriculture, I found that each domain has something to offer when thinking about what the core challenges are, how to approach them, and what to actually do about them.

In this chapter, I do not endeavor to present a systematic literature review. Instead, I offer a selection of related work (Section 2.1) that provides the reader with sufficient background to engage in the various topics covered over the next five chapters. In Section 2.1.1, I describe work conducted by researchers in the domain of agriculture, many of whom are engaged in modeling- and software-oriented activities. Next, in Section 2.1.2, I describe work conducted within the software community that is concerned with design for agriculture. Finally, as the work I describe in this dissertation is scope to focus on California agriculture from Chapter 4 onwards, Section 2.1.3 provides some policy and regulatory context on agriculture in California.

This chapter concludes with the theoretical framing that guides the work presented in this dissertation (Section 2.2).

2.1 Related Work

2.1.1 Modeling Agricultural Systems

Software systems for agricultural modeling are primarily designed for activities such as farm simulation [120] and yield maximization [210]. These can be both computationally (and financially) expensive. Such work, while interesting, relevant, and timely, primarily addresses the modeling and simulation of agricultural systems to improve crop yields and system management, with only a marginal focus on environmental assessment of these systems.

Agricultural Ontologies: The Food and Agriculture Organization of the United Nations has maintained the AGROVOC project since the 1980s [6]. It is a controlled vocabulary, designed for, and used by, information management professionals (primarily librarians and researchers). It consists of over 32,000 agricultural concepts, gleaned from publications, research artifacts, and external thesauri. Similarly, the United States Department of Agriculture's National Agricultural Library has provided a more America-centric glossary and thesaurus service since 2002 [237]. These initiatives are part of a broader goal within the agricultural information management community to standardize agricultural terms, concepts, and data. There are also several efforts — in early stages of development — to extend tradition agricultural thesauri into fully developed ontologies for use at the farm level to inform crop production [17], "foods-for-health" knowledge systems in the nutrition space [125], and to augment precision agriculture with plant-driven decision making capabilities [90]. The AGROVOC team is also developing an ontology service in anticipation of semantic web requirements [128].

Crop Modeling: Work in crop modeling tends to focus on operational and yield optimization. For example, Honda et al. [107] present a service platform that uses a network of field sensors (aircraft and ultra-light vehicles) to obtain real-time field data to plan large-scale field operations e.g. fertilizer application. Meanwhile, Ponti et al. [56] used statistical models to assess the yield gap between organic and conventional agriculture to obtain a deeper understanding of the range of performance in agriculture.

Agricultural Simulation: Agriculture researchers often use simulations to understand and make predictions about the performance of various agricultural systems, while computation researchers apply their expertise to improving the performance of simulations in agriculture. For example, the Agricultural Production Systems sIMulator (APSIM) project [120] is a modular simulation tool that allows for the investigation of relationships between plants, animals, soil, climate, and management involved in agricultural systems. Papajorgji et al. [164] present different ways in which model-driven architecture, in particular the use of the Unified Modeling Language, can be leveraged to improve crop simulation models. Miralles & Libeourel [149] study how Geographic Information System models can be brought to bear on crop simulation to allow for better integration of weather data.

Life Cycle Assessment: LCA is a modeling technique used to assess the environmental impacts of products and the processes by which they are constructed [190]. Farmers, along with environmental analysts, can conduct LCAs to quantify the environmental impacts of resource flows in a system, and subsequently make improvements in the farming processes to reduce undesired impacts [96]. Many software systems [213, 194, 94] and databases [95, 179, 157, 62] exist to support LCAs, most of which are domain agnostic (i.e., not designed for any particular domain, including agriculture).

Models of agricultural products and production systems are commonly created in the academic community using LCA. Examples of systems that have been successfully analyzed using LCA include: a large American feedlot where beef is produced [167]; a soybean meal production chain that spans from Argentina to Denmark [54]; and an Australian corn chips production chain that begins at the corn farm, and ends at the consumer-ready packet [92]. While LCA models are intended to provide efficient and convenient access to information about the environmental performance of production systems, such as agricultural systems, there is a disconnect between the current LCA modeling process, the needs of sustainable farmers, and the systems represented.

2.1.2 Design for Sustainable Agriculture

The Bruntland report presents an umbrella definition of sustainable development as, "the ability of humanity to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs" [26]. While this definition is commonly used in sustainability research, it is too broad to allow us to engage in grounded, sustainable, human computer interaction (HCI) work, or other forms of sustainable design activities. We often come away from such discussions with difficulty envisioning specific applications to design and actionable interventions to pursue [169].

There have been many explorations of sustainability in the context of HCI, ICT for Development, and the coordination literature. However, just as most "sustainability-oriented work takes place outside HCI" [193], much design work for sustainable agriculture also occurs at the periphery of applied computing research. In this section, some of the more promising explorations within this periphery are reviewed.

HCI and Agriculture: Interest in the intersection of HCI, design, and agriculture [162, 172, 204, 246] is growing. For example: Raghavan et al. [180] recently suggested use of computation to design better agro-ecological systems, and Frawley & Dyson created non-human animal personas to enhance welfare in animal agriculture [77]. For the most part, design for agriculture tends to be for specific subsets of agriculture. For example, Chinthammit et al. [48] ran a Software Interest Group meeting, looking at "HCI in Food Product Innovation". Whether it is design ideations specifically for urban residential gardeners [136] or the design of platforms to assist in the creation of backyard permaculture systems [160], Di Salvo et al. point out that "there is a significant gap between the professional fields of industrial and interaction design and design research in sustainable HCI" [59]. In an attempt to bridge this gap, my collaborators and I ran a workshop on at the ACM CHI conference in 2017 on "Designing Sustainable Food Systems" [181]. We aimed to bring together HCI researchers, designers, and practitioners to explore, design for, and reflect on, opportunities for the HCI community to engage in creating more a sustainable food system.

Coordination and Collaboration in Agriculture: Food production is an inherently collaborative process, with many stakeholders involved and varying organizational configurations across system types. Examples include: a qualitative study looking at coordination challenges in organic farm families [133], and an early warning management technique to enable collaboration among rice farmers participating in small-scale precision agriculture [11]. Such work provides valuable context for understanding how the interplay between stakeholders on farms affects tool design.

Farm Management: At the time of this writing, the Information Technology startup community began focusing on the design of tools for agriculture. Earnest examples include: precision farming tools [115, 5, 69], precision agriculture tools requiring specialized hardware [174, 25]; daily farm management tools aimed at agribusiness [50, 93, 4, 2, 163, 71]; inventory management tools [16]; and tools that provide analytics [68, 7, 70].

2.1.3 California Agriculture

Agricultural Environmental Policy: Environmental regulations have serious implications on farm-level assessment, data collection, and record keeping that farmers in California must engage in [38]. Regulations, both state-imposed [200, 226], and federal [225, 224], typically require some form of record keeping and form filling, and in some cases, the presentation of these documents during site inspections. Environmental policies that California farmers are subject to include: water [200], pesticides [225, 224], and emissions [226] regulations. In addition, farmers may participate in voluntary programs to demonstrate commitment to environmental protection, such as the environmental stewardship program [241].

Environmental Labeling and Certification: The primary goal of environmental labeling and certification agencies is to provide farm quality assurance [129]. These labels and certificates provide the purchaser, whether broker, retailer, or consumer, with the validation that a farm meets a particular standard set out by the certifying agency. The efficacy and usefulness of labels has long been debated from the early days of dolphin-safe labels [208] to the present-day quandary of GMO-labeling [253]. Nevertheless, many farms actively pursue labels and certifications, necessitating an additional layer of record keeping and data collection.

There are four main types of labeling and certification in sustainable agriculture: government-regulated (e.g., United States Department of Agriculture's (USDA) National Organic Program [231]); non-profit regulated (e.g., Certified Naturally Grown [45]); retailer specific (e.g., the Whole Foods sustainability rating [250]); and product-specific (e.g. the Certified Humane label [44] for livestock).

2.2 Theoretical Framing

To explore the challenges that exist in modeling sustainable agriculture, I first, characterize the environmental assessment process as a modeling process, and secondly, characterize sustainable agricultural systems as complex adaptive systems.

2.2.1 Modeling Theory

In this section, the environmental assessment of agricultural systems is cast as a modeling technique. Statistician George Box said, "Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful" [29]. One of the goals of this dissertation is to see how environmental impact models can be made more useful through the rigorous application of modeling theory to the essential difficulties involved in the modeling of farms.

The Nature of Models: Modeling is the process of abstracting a system in the real world, such that only the attributes pertinent to a particular analysis remain. Components in a model, therefore, represent attributes of the original system that contribute information relevant to the goals of the modeling process [135]. These goals include the identification of trends, patterns, or generalizations that can then be used to understand or improve the original system. In this dissertation, I consider the modeling of agricultural systems to investigate their environmental impacts.

The word *model* is a loaded term that can mean a multitude of things depending on the nature of the problem and the application domain. In this dissertation, *model* refers to a representation model, i.e., one that is a "representation of a selected part of the world (the 'target system')", as opposed to models that represent sets of laws and axioms that constitute a theory (e.g., Euclidean geometry) [78].

Two categories of representational models exist: those that represent the phenomena occurring within complex systems and those that represent the data constituting the states within said systems. A datapoint can be thought of as an observation or measurement at a particular point in time and space of a particular phenomenon. Examples of this data-phenomena relationship include: observing a person's mood [data] over the course of a day to investigate effects of fatigue [phenomena], measuring temperature [data] to predict the weather [phenomena], or monitoring energy consumption by a computer server [data] to dynamically balance power loads [phenomena]. The real world, however, is not always neatly separable into phenomena and data.

The General Modeling Process: Models are often used to perform a particular analysis to produce a result, such as the identification of trends, patterns, or generalizations that can then be used to understand or improve the original system. Ideally, the results of a modeling exercise lead to the production of knowledge that can help answer related questions; create, improve or understand similar systems; and add to the overall understanding of the real world.

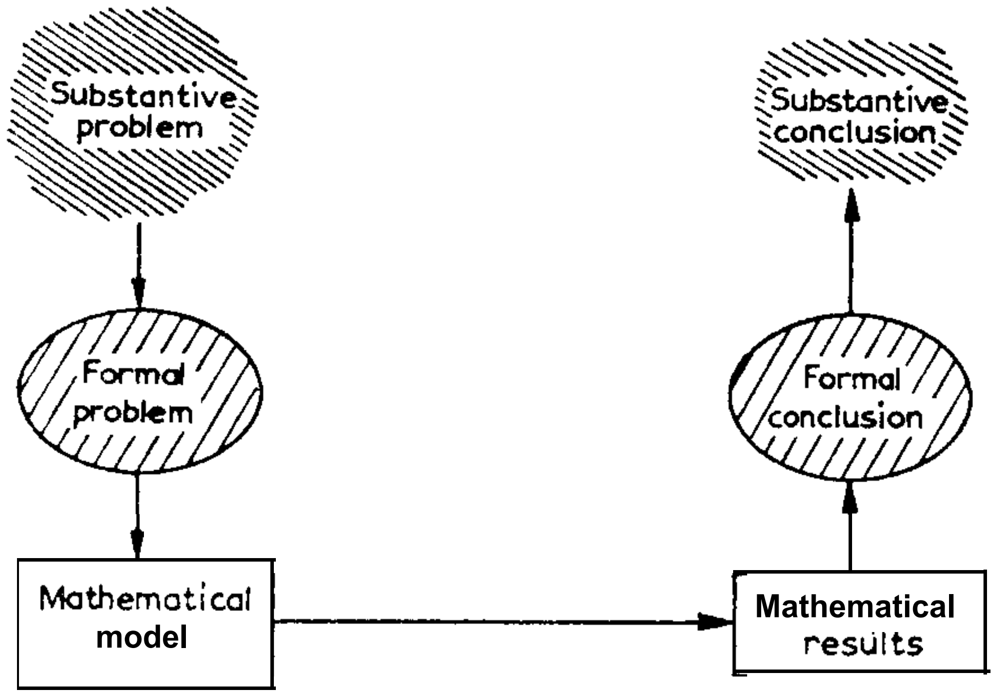

Figure 2.1: Strauch's general description of the quantitative modeling method [202].

The modeling process, as described by Strauch [202], can be viewed as a three tier process shown in Figure 2.1. It begins with describing a substantive problem, an issue in the real world that determines the goals and questions of the analysis. Next, the problem is formalized using methods specific to the problem domain. Finally, a mathematical model can be created, perhaps as a set of equations describing the problem, to provide quantitative mathematical results. These are then analyzed to produce a formal conclusion, which is then applied back to the problem domain to produce a substantive conclusion: a solution in the real world.

This process works well for well-defined problems that can be scoped, where components of a model can be measured and counted. However, problems in the real world are, as Strauch would say, "squishy" [202]: they do not necessarily have a well defined structure with clear cut boundaries. Squishy problems abound in modeling agriculture, the environment, and software.

To address this squishiness, informal methods and qualitative analysis techniques help transition the problem to a formal model, and back to a substantive conclusion. This dissertation deals with the squishiness of agricultural systems and the issues that arise when modeling their environmental impacts.

Models in Software Engineering: In Software Engineering (SE), models are created to "help software engineers understand, engineer, and communicate aspects of the software to appropriate stakeholders" [196]. Many different types of models are created, with various roles in the software development life cycle, and for capturing different aspects of a software system to be constructed. Three broad types of models are described in the Software Engineering Body of Knowledge [196]:

1. Information models: These represent data and information related to the software to be modeled, including concepts, properties, relationships, and constrains on data entities.
2. Behavioral models: These represent functions of the software to be modeled, and take the form of state machines, control-flow models, or data-flow models.
3. Structural models: These represent the physical or logical composition of the software to be modeled using constructs such as composition, decomposition, generalization, etc.

These three types encapsulate both phenomena and data. A multi-model approach is taken in SE, where models are used to describe a software system and each model describes a certain aspect of it: For example, Entity-Relationship (E-R) models are commonly used to statically represent data, while Data Flow Diagrams (DFD) dynamically capture processes. Both views are complementary perspectives of a system. Pastor & Molina state "A classic example of [the strong relation between models] is... that every entity of an E-R Model is used in a process of a DFD" [165].

Object-Oriented Modeling: The Object-Oriented (OO) paradigm has been successfully used to address the squishiness inherent in modeling software. The OO modeling process involves three major activities:

1. Analysis: "A method of analysis that examines requirements from the perspective of the class and objects found in the vocabulary of the domain" [27].

2. Design: "A method of design encompassing the process of object-oriented decomposition and a notation for depicting both logical and physical as well as static and dynamic models of the system under design" [27].

3. Programming: "A method of implementation in which programs are organized as cooperative collections of objects, each of which represents an instance of some class, and whose classes are all members of a hierarchy of classes united via inheritance relationships" [27].

This triad forms the essence of the Object-Oriented Modeling (OOM) process, through which software models are iteratively refined as one moves through the cycle shown in Figure 2.2.

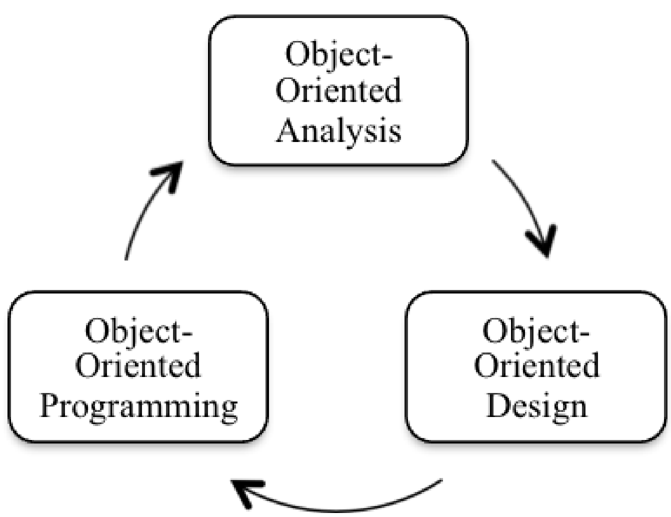

Figure 2.2: Object-Oriented Modeling (OOM).

OOM is often used to create prescriptive models of a system to be implemented (the user needs); it can also be used to reconstruct models of existing systems for analysis. Traditionally, products of each phase are descriptive models for the next (Figure 2.3) [135]. OOM results in models that are represented linguistically (e.g., requirements documents), static and dynamic models (e.g., class diagrams, sequence diagrams), and sometimes prototypes of the software system to be constructed.

These models are typically presented in the specification, architectural design, and detailed design documents of the software modeling document chain diagram in Figure 2.3. Object-Oriented Programming (OOP) involves converting these models into working code that represents the underlying object model of the software system (source code and below in Figure 2.3).

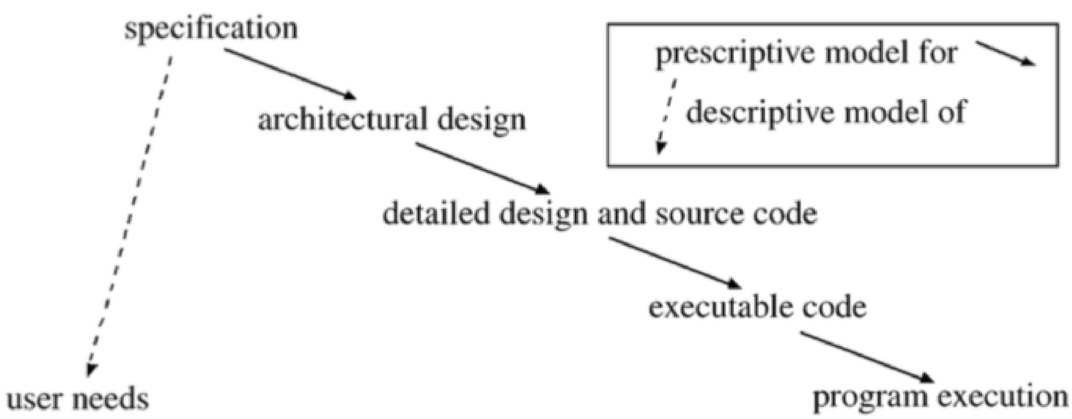

Figure 2.3: The software modeling document chain [135].

A modeling language is defined by its syntax, or notation, that is used to describe the model, and its semantics, or rules that govern how concepts can be related. A good modeling language has clear and understandable syntax, as well as a distinct mapping from the semantics to the domain in which the modeling process is being conducted [37]. Booch states:

> *"The object model encompasses the principles of abstraction, encapsulation, modularity, hierarchy, typing, concurrency, and persistence. By themselves, none of these principles are new. What is important about the object model is that these elements are brought together in a synergistic way."* [27]

A good OO modeling language must therefore support, at the very least, abstraction, encapsulation, modularity, and the creation of hierarchies. The Unified Modeling Language (UML) is the de facto standard for modeling software systems, particularly in OOM [161, 124, 28]. Notably, UML used in OOM has proven to be a good software modeling language. UML enables the representation of the object model in a synergistic way. UML is largely successful as:

- UML upholds OOM principles of abstraction in addition to having support for modeling complex systems [191], support for hierarchic structures [188], and encouraging the separation of concerns [123].
- UML supports modularity by allowing for representation at varying levels of system granularity [161], allowing for design of modular OO components [86], providing structure for definition of interfaces [188], and having both static (structural) and dynamic (behavioral) views [192].
- UML provides the capacity for holistic understanding of a system by allowing for varying degrees of formality [28, 85], and encouraging traceability between models [81].
- UML has a very well defined and standardized language [192], with wide variety of tools for the modeling of software systems [142, 211, 247].

The power of the object-oriented paradigm, as described by Pastor & Molina, is that "it attempts to capture reality as it is, composed of objects that are data and processes that altogether result in a synergistic whole" [165].

2.2.2 Complex Adaptive Systems

A complex adaptive system is is one that exhibits heterogeneity and nonlinearity in system components, interdependencies among systems, natural groupings and hierarchies among systems, feedback and looping among subsystems, and emergent properties [150, 135].

In a 2015 report, "A Framework for Assessing the Effects of the Food System" (hereafter the 'National Academies Report'), a committee of researchers and domain experts detail, "a tool for decision makers, researchers, and other stakeholders to examine the possible impacts of interventions and evaluate the collective health, environmental, social, and economic outcomes of specific changes in the food system" [110]. The authors characterize the "U.S. Food and Agriculture System" as a complex adaptive system. First, they describe five characteristics of complex adaptive systems:

1. Individuality and Adaptation: There are many actors (including humans) participating in the system, each with individual goals, actions, and needs. Each of these have different processes of adaptation and mechanisms to deal with change. In turn, each of these actions have their consequences.

2. Feedback and Interdependence: There are many mechanisms and pathways within the system: among actors, sectors, and factors; across different scales; and across spatial and temporal bounds. These result in feedback loops and interdependence between system components. These feedback loops can be positive or negative, and these interdependencies can be more or less complex.

3. Heterogeneity: System actors and processes are heterogenous. There is variability within populations, within groups of actors, and even within a particular type of actor. There is variability in their actions, in system processes, and in the resulting system behaviors.

4. Spatial Complexity: The complexity of the spatial dimension of the system consists of more than just geography. There are varying spatial structures including supply chains, industry sectors, environmental contexts, proximities to other systems, and borders between systems.

5. Dynamic Complexity: This system contains feedback loops, and interdependence between activities, and adaptive responses by actors. These can be in the form of nonlinear pathways and emergent system behavior.

Then, the authors of the National Academies Report [110] further present a framework for rigorous and holistic system analysis of the environmental, health, social, and economic effects of the food system. They describe four key principles:

1. consideration of complete supply chains,
2. consideration of all dimensions of sustainability and orders of effect,
3. accounting for the complexities and dynamics exhibited by a complex adaptive system, and
4. the selection of problem- and domain- appropriate analysis techniques.

In this dissertation, I characterize small- to medium- scale agricultural systems as complex adaptive systems. While I adopt this characterization, the scope of this work does not allow for full adherence to the key assessment principles put forward in the National Academies Report [110]. Instead, this dissertation:

1. considers only the farm component of the supply chain, with the acknowledgement that the farm is a component of the larger food system,

2. considers issues regarding environmental sustainability, with the acknowledgement that other dimensions of sustainability are closely intertwined,

3. accounts for the complexities and dynamics exhibited by agricultural systems as complex adaptive systems, and

4. considers and supports problem- and domain- appropriate analysis techniques.

Therefore, the work presented in this dissertation, particularly the modeling framework proposed in Chapter 5, is focussed on modeling the complexities and dynamics of agricultural systems, in the context of issues regarding environmental sustainability, the position of the farm in the greater food system, and given the variety of farm-level assessment techniques that have been developed. The framing of sustainable agricultural systems as a complex adaptive systems allows for both the exploration and unpacking of the dynamics and complexities of these otherwise "squishy" [202] systems.

Chapter 3

Formal Modeling in Agriculture

In response to growing concerns regarding the sustainability of human civilization, rising effects of climate change, and worldwide resource inequalities (including energy crises), researchers have developed a variety environmental impact assessment techniques to reduce and manage the environmental footprint of human-made systems. One technique in particular, Life Cycle Assessment (LCA), is used to investigate the environmental impacts of industrial products and production systems [55]. Major issues such as water pollution, greenhouse gas emissions, and eutrophication tend to be a result of resource intensive processes such as the extraction of raw materials, consumption of materials and energy, transformation of one material into another, and the manufacture of products. LCA involves the quantification of these resource flows (inputs and outputs to a process) in a system to calculate the environmental impacts that the system incurs.

Models of agricultural products and production systems (e.g., farms) are commonly created using LCA. Farmers, along with environmental analysts, can conduct LCAs to quantify environmental impacts, and subsequently make improvements in the farming processes to reduce undesired impacts [96]. Interest in tailoring LCA for agricultural systems has led to the identification of many substantive problems at the intersection of agricultural modeling and environmental impact assessment. This has led to the development of many new modeling techniques, creation of software tools, and interdisciplinary collaborations. As a result, myriads of models are produced to address these problems.

The creation of LCA models is often money and time intensive, requiring input from many stakeholders, large quantities of data to be collected, and analyses to be conducted by environmental experts trained in LCA methods and tools. The resulting LCA models are instrumental to understanding and improving the environmental performance of the agricultural system of interest. These LCA models are therefore highly place and time specific: they often represent a single product system in a particular geographic region using data collected during a certain period of time. By the time the environmental impacts are calculated and translated into meaningful recommendations for a change in the real world system, the models may be out of sync with the real world. This is not conducive to making recommendations regarding the assessment, design, or optimization of other similar systems.

The primary research question underpinning this chapter is:

> How are agricultural systems modeled in order to enable environmental impact model their agricultural systems to assess environmental performance?

Specifically:

1. How can one compare among and connect across different LCA models, representing different products, production systems, geographic regions, and industrial sectors?
2. How are agricultural systems represented, and how can these models be compared and connected?

3. How can one maintain data within LCA models, and update the structures of these models, as the real world systems they represent change over time?

4. How are changes in agricultural systems represented and tracked?

Chapter Overview: This chapter is laid out as follows: Section 3.1 overviews the generic LCA process. Section 3.2 LCA methods through an overview of a selection of LCA studies. Section 3.3 presents the various models, data, and tools used in agricultural LCA. Finally, Section 3.4 analyses the capacity of LCA to model the environmental impacts of sustainable agricultural systems through scenario-based modeling.

3.1 Life Cycle Assessment (LCA) Overview

LCA is a technique used to assess the environmental impacts of products and the processes by which they are constructed [190]. The system of interest typically involves the development of a particular product: a farm where tomatoes are grown [12], a factory where shoes are made [186], or a wastewater treatment plant where clean water is produced [205]. There exist numerous LCA variants. Each has a different purpose, system modeling technique, domain applicability, and data requirements.

Standardization: The generic LCA process is governed by a suite of standards: ISO 14040 details the principles and overall framework [111], and ISO 14044 [112] specifies the requirements and guidelines for conducting an LCA. These standards are part of a greater family, ISO 14000, regarding Environmental Management, that provide guidance on environmental assessment, performance, and responsibility [114]. ISO standards are reviewed every five years: the most recent versions of ISO 14040 and ISO 14044 were published in 2006 and reviewed in 2010. These reviews aim to maintain the capacity of LCA models to represent systems resulting from advances in the real world.

Not all LCA studies are ISO compliant. However, compliance tends to occur in government funded LCAs, when analysts intend for their data to be incorporated into national LCA databases (discussed later), some LCA research, and certain LCA studies conducted for companies and organizations. LCA standards are written in a domain agnostic manner, enabling for LCAs conducted in any domain to potentially be ISO compliant. For instance, an LCA of a beef producing agricultural system [167], plastics and metals recycling [79], and a printer cartridge [76] can all be ISO compliant, as long as they adhere to the requirements and guidelines laid out in ISO 14040.

For the rest of this section, I will briefly overview the generic LCA process. Figure 3.1 outlines the main phases of an LCA: Goal Definition and Scope, Inventory Analysis, Impact Assessment, and Interpretation. There are varying techniques for conducting both the overall LCA, as well as individual phases.

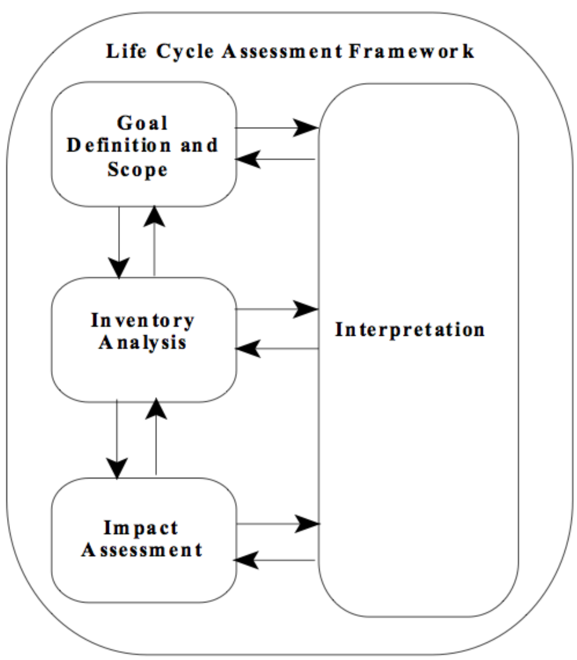

Figure 3.1: Phases of an LCA, ISO 14040 [111].

3.1.1 Phase One: Goal Definition and Scope

The first step of conducting an LCA involves articulating the goals of the assessment and scoping the system to be assessed.

Define the purpose of the LCA study: One is describing a problem in the real world: what environmental impacts are incurred by producing specific quantities of a product, how great are the impacts (for example, what quantities of pollutants are produced), and what are the causes? Therefore, the goal is to assess the environmental footprint of the system. Alternatively, the goal could be to compare the environmental performance of competing systems. Depending on the problem domain, reasons for the analysis being conducted, and the familiarity of the analyst with the domain, the analyst may, from experience, know which environmental impacts can and should be calculated. There exist environmental impact categories that can be selected as specific areas of interest, but they are not always selected during Phase One, as they are only used in Phase Three when impact calculation occurs.

Define system boundaries and scope: The production systems and stages to be included in the system of interest, and therefore the assessment, must be selected.

For example, a *cradle-to-grave* LCA includes everything that went into the manufacturing of the final product, starting from the extraction of raw materials, to the disposal of the product after use. It takes into account the full life cycle of a product. This also requires specifying the time scale of the analysis: for example, the life cycle of a solar panel includes 25 years for the operational/use phase, in addition to the time spent in the manufacture and disposal of the product [119]. In contrast to the solar panel, the use phase of a cup of coffee depends on how it is made and consumed [108]. The under*cradle-to-grave* LCA stages for which raw materials and energy are accounted for are: raw material acquisition, transportation, manufacturing processes, the use, reuse, and maintenance of the product, and finally, recycling and waste management [190].

Alternatively, a *cradle-to-gate* LCA, accounts for everything up until the product is ready to be transported to the customer. This method of scoping an LCA study works particularly well for analyzing production systems for physical products with a well-defined life cycle, clear-cut inputs and outputs, and a limited set of uses. More recently, it has been suggested that life cycle considerations should extend from "cradle-to-cradle" [140], taking into account both the production, but eventual disposal, and potential reuse of physical products.

A decision must also be made as to how many levels of indirection from the core system are to be included in the study.

Attributional LCA studies focus on accounting only the immediate and direct impacts of the system of interest [74]. This has been the traditional approach to LCA, where one quantifies the effects of the system as it currently is.

On the other hand, *consequential* LCAs take into account environmental impacts that are incurred externally by the internal processes of the system of interest [74]. For example, in the study by Dalgaard et al. [54], they perform a consequential LCA of the production of soybean meal in Argentina, and its subsequent importation to Denmark. They ask:

> *"What is affected by a change in demand? For example, when impacts related to electricity input for a certain unit process are considered the question is: what are the environmental consequences related to a change (typically small) in the demand of electricity in this market?"* [139]

In a *consequential* LCA, only the processes that may encounter a change — the "affected processes" [74] — are considered in scope. This requires a certain amount of foresight that is sometimes difficult to quantify. It requires knowledge of the product life cycles of other systems that induce indirect changes in the system of interest and vice versa. The decision of *attributional* versus *consequential* LCA therefore comes down to how broad of a scope the study is intended to have. The analyst must decide how far reaching of an impact to consider in the LCA study.

The scope and boundaries of an LCA study determine which processes will be considered when finally doing the environmental impact assessment.

> *"It would be nonsensical to compare a disposable paper cup with a china cup, given that the life span of the two differs by a factor of at least 100. Instead, the function of the two alternatives, such as drinking one cup of coffee, could be compared. The function to be compared is referred to as the functional unit."* [108]

Select a functional unit: The choice of unit is determined by factors such as; the stages considered in the life cycle, the time scales involved, the type of system under study, the goals of the study (is it intended to be a comparative study?), among others [182]. In addition, there are sometimes "midpoint" functional units that are used for analyzing parts of the system — for example, to connect partial products that are extracted or manufactured in different stages [39]. The functional unit may be used as a conversion unit to enable analysts to compare systems. For example, consider two systems: apple orchard A where the final product is whole fruit; and apple orchard B, where the final product is a variety of apple products such as jams and juices. If both systems have a functional unit of 1 pound of apples, one can still compare the carbon footprint of each system, albeit one would scope the systems at the point where whole apples are harvested.

3.1.2 Phase Two: Life Cycle Inventory (LCI) Analysis

The Life Cycle Inventory (LCI) Analysis phase involves gathering a list of all the processes occurring within the system, along with the material and energy resources utilized, useful products created, and waste produced. In this phase, the system of interest is decomposed into a set of discrete processes, with inputs, outputs, and quantifiable flows of material and energy resources through each process. A comprehensive LCA relies on the ability of the analyst to find the environmental impact of each process within each subsystem during the LCI Analysis phase. This approach is known as *process* LCA.

Alternatively, in an *input-output* LCA, the system is treated as a whole, with aggregate inputs and outputs into the system. One of the most popular variants is the *economic input-output* LCA [104] (EIOLCA): it uses aggregate economic inputs and outputs into the system of interest to estimate environmental impacts. It is an application of a popular economic modeling approach that is used to assess the economic performance of a system (e.g., a country) [132].

This phase has two deliverables. The first is a flow diagram, a high level overview of the main processes or components in the system. The second is the Life Cycle Inventory itself. The LCI is an all-encompassing inventory of inputs, outputs, and processes within the system of interest.

Process and *input-output* LCA represent two different approaches to abstracting the system of interest into a model with quantitative and qualitative attributes. The level of detail in an LCA study also varies based on how much time, effort, and money the analyst has to put in, how much data is actually available or collectable, and what the results will be used for. If the level of detail is low, and the system of interest has been simplified in its representation, the study is labeled as a *streamline* LCA. Otherwise, every process of every stage in the scope of the system of interest must be represented in the LCI.

3.1.3 Phase Three: Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) phase is where the main analysis of the product system occurs. The LCA ISO 14044 standard specifies mandatory elements within this phase [112]: the selection of impact categories, category indicators, and characterization models; classification (the assignment of the LCI results); and characterization (calculation of the category indictor results).

This produces a set of Category Indicator Results, which collectively are known as the LCIA Profile, and where each result represents the actual environmental impacts of the system of interest by associating each of the processes in the LCI with the impact categories affected by the process. Impact categories may include: eutrophication, climate change, global warming potential (GWP), land use, water use. There has also been growing interest in conducting more holistic "sustainability" LCAs [73] that include assessment with respect to economic, social, and environmental sustainability, as described by Goodland [87].

The functional unit, the processes represented in the LCI, and selected impact categories are brought together in this phase to produce system level calculations of environmental impacts. Conclusions take the form of: *X system causes Y quantity of Z impact, due to [1:n] processes.*

3.1.4 Phase Four: Interpretation

The interpretation phase of the LCA involves analysis of the results after each phase, validation to ensure that the LCA is proceeding in compliance with the originally stated method, and creation of reports regarding progress and findings. According to the ISO 14040 standard, this phase involves the reflection on the results of the Life Cycle Inventor Analysis and the Life Cycle Impact Assessment, as well as appropriate communication about findings [111].

While there are many interpretation activities within this phase, they are usually specific to the types of environmental impact that are being calculated in a particular life cycle assessment case. Interpretation involves the production of a variety of charts and reports communicating intermediate results and checking in with the stakeholders of the study to ensure correctness and completeness. This is not actually the last phase of LCA, but instead, it occurs after each of the other phases. It allows for constant reflection on the relationships between results in different phases as they are produced.

3.2 LCA Methods for Agriculture

3.2.1 Search Method

The studies analyzed in this section were constrained to those whose primary focus was on the United States, European or Australian agricultural systems, due to two reasons. First, a vast majority of published LCA literature is in English, and comes from these three regions. Second, while LCA is popular in other parts of the world, such publications are not always easily accessible, or data sources traceable, as they may be using local databases or native language resources.

Figure 3.2(page 35) describes the top ten most produced agricultural commodities globally, as reported by the Food and Agriculture Organization of the United Nations Statistics Division. As some of these foods are produced primarily outside of the regions of interest in this paper (United States, Europe, and Australia), they were cross referenced with the top ten most produced agricultural commodities in each of those regions to create a list of commodities to be considered in this paper.

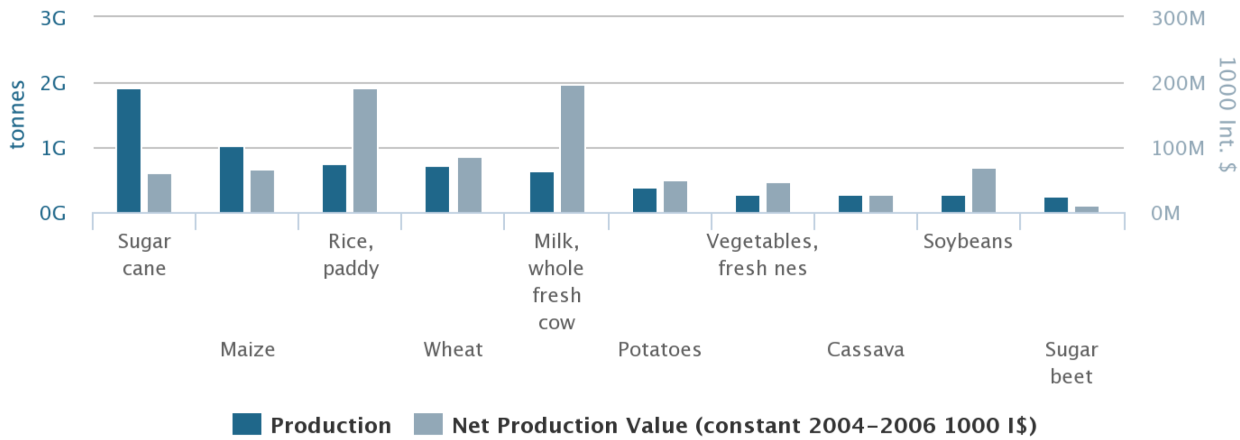

Figure 3.2: Top 10 food and agricultural commodities globally [75].

Table 3.1 (page 36) shows which of the globally most produced food and agricultural commodities are also in the top ten most produced commodities of the United States, Europe and Australia. Note that some commodities, such as rice, vegetables, and cassava, are not widely produced in any of these geographic regions. Therefore, commodities of interest were those that existed in the both the global top ten most produced and the top ten list of at least two out of three regions.

Figure 3.3 (page 36) shows that enteric fermentation and three manure related activities (manure management, manure left on pasture, and manure applied to soils), contribute 66.1% of agriculture's emissions, resulting in significant interest in better understanding the environmental impacts of livestock farming. Beef is one of the top ten most produced commodities in both the United States and Australia. Similarly pork is one of the most produced commodities in Europe. As they are therefore responsible for a large proportion of global agricultural emissions, these two livestock farming commodities, beef and pork, were added to the list of commodities of interest in this paper.

Table 3.1: Commodities that are both most-produced globally as well as one of the top ten most-produced commodities in each of the regions of interest (data source: [75]).

Commodity	United States	Europe	Australia
Sugarcane	✓		✓
Maize / Corn	✓	✓	
Rice			
Wheat	✓	✓	✓
Milk	✓	✓	✓
Potatoes	✓	✓	✓
Vegetables			
Cassava			
Soybean	✓		
Sugarbeet	✓	✓	

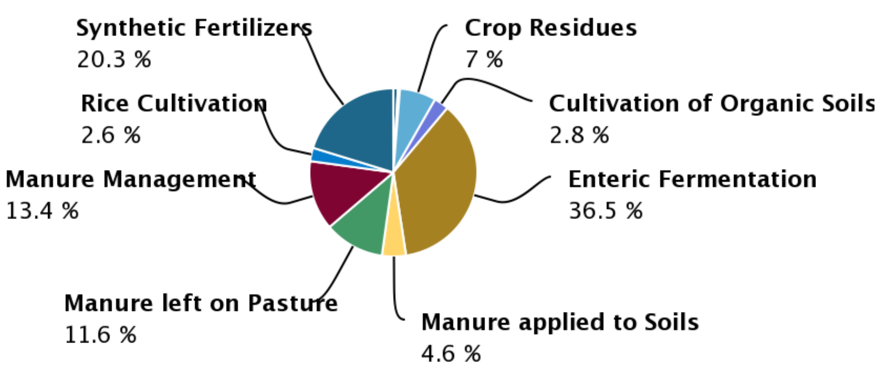

Figure 3.3: Global emissions by sector (Average 1990 - 2012) [75].

Thus, the primary inclusion criterion for LCA studies in this dissertation is: *Is the primary product {sugarcane, corn, wheat, milk, potatoes, sugar beet, beef, pork}? AND Is the system located in {United States, Europe, Australia}?* A second set of papers was snowball sampled: they covered multiple products and/or spanned multiple geographic regions, and discussed a new aspect of the problem domain. As such studies are rare, there were two additional inclusion criteria: *Are any of the products {sugarcane, corn, wheat, milk, potatoes, sugar beet, beef, pork}? OR Are any of the systems located in {United States, Europe, Australia}?*

3.2.2 LCA for Agriculture Literature

The resulting set of LCA studies that are used for the analysis in this section are summarized in Table 3.2. It should be noted that for each of the LCA studies referenced, several other studies exist that look at the same crop produced in a different agricultural system, geographic location, time period, or using different farming techniques. This section is not intended to provide a comprehensive review of every single LCA study of agricultural systems, rather it aims to demonstrate the nature of LCA models that result from a diverse range of studies.

Table 3.2: Summary of LCA studies.

Product(s)	**Location(s)**	**Goal of Study**	**Ref**
Beef	Canada	Comparison of feedlot systems through the LCA of simulated farms.	[21]
Beef	USA	Comparison of alternative beef production (feedlot, feedlot and pasture, pasture only) methods.	[167]
Corn	Australia	Analysis of a production chain from farming of corn to make processed corn chips.	[92]
Corn	USA	Comparison of two cropping systems: 1. Corn produced for grain only, 2. Corn grain and stover (residue e.g., husk, leaves) harvested.	[121]
Milk	Netherlands	Comparison of conventional versus organic dairy farms.	[215]
Milk	Sweden	Comparison of conventional versus organic dairy farms.	[39]
Milk	USA	Analysis of milk production chains to create a baseline data for future LCAs.	[214]
Pork	Australia	Comparison of conventional versus alternative pork production (waste management related) methods.	[251]
Pork	France	Comparison of conventional versus alternative pork production (Good Agricultural Practices, Red Label, Organic) methods.	[19]

Continued on next page

Table 3.2 — continued from previous page

Product(s)	Location(s)	Goal of Study	Ref
Potato	Sweden	Analysis of uncertainty quantification LCA methods through the LCA of a potato production chain.	[187]
Sugarbeet	Germany	Analysis of sensitivity of LCA methods through the LCA of similar sugar beet production chains.	[30]]
Sugarbeet	UK, Germany	Comparison of Genetically Modified versus traditional sugarbeets.	[22]
Wheat	Switzerland	Comparison of different functional units through the LCA of wheat farming.	[46]
Wheat	USA	Analysis of a wheat production system to update energy impact data available for other LCAs.	[173]
Wheat	USA	Comparison of conventional versus organic wheat production.	[141]
Multi-product or multi-region systems:			
Beef, Milk	Sweden	Comparison of co-product allocation LCA methods through the LCA of a beef-milk farm.	[40]
Beef, Mutton	Australia	Comparison of alternative production methods for red meat.	[171]
Broccoli, Salad crops, Legumes	UK, Spain, Uganda, Kenya	Comparison of domestic versus imported vegetables through LCAs of the different cropping systems and supply chains.	[146]
Rapeseed, Oil palm, Soybean,	Sweden, Malaysia, Brazil	Comparison of three cropping systems, where the crop is processed into vegetable oil.	[139]
Salmon	Canada, Chile, Norway, UK	Comparison of four salmon farming systems, to find shareable good practices from different regions.	[168]
Soybean	Argentina, Denmark	Analysis of a soybean meal production chain that begins in Argentina and ends in Denmark, to produce baseline data and test LCA methods.	[54]

Continued on next page

Table 3.2 — continued from previous page

Product(s)	Location(s)	Goal of Study	Ref
Sugarbeet, Sugarcane, Corn	UK, Australia, USA	Comparison of three cropping systems, where the crop is processed into sugars for fermentation.	[183]
General*	Australia	Comparison of conventional versus organic farming.	[252]
General*	Germany	Comparison of intensive, extensified (land use intensity), and organic farming of crop and cattle.	[97]
General*	USA	Analysis of the US food system through LCA to connect different agricultural sectors.	[102]

* Farms were treated as general cropping systems with no specific set of commodities.

Four categories of LCA studies were found:

1. Comparative: study involved comparing two or more production systems with respect to their environmental performance;

2. Connective: study involved connecting two or more production systems to create a more holistic understanding of environmental performance;

3. Update: study updating current LCA data for a particular system type, location, or production method;

4. Methodology: study related to improving the performance of the LCA method, where the LCA conducted tests the proposed changes.

Most of the LCA studies found, 18 of the 25, were comparative studies. Many looked at the differences between conventional and organic farming systems. As there is a current push toward both growing and buying more organic food, it makes sense that the community is interested in finding empirical evidence to support the environmental benefits of organic food. Comparisons of different cropping systems that result in a similar processed product is also common: For example, three cropping systems (growing rapeseed, oil palm, and soybean) are compared, as all three result in the production of vegetable oil [139]. In all of the studies in this category, the agricultural systems are manually compared.

Surprisingly, there were only two connective studies and one update study found. It may be the case that updates to LCI data are not commonly published in academic literature, and are instead directly updated in LCI databases (more on these databases in Section 3.3.3). The lack of papers in the connective category may be evidence that there truly is a lack of connectivity across the plethora of LCA models created.

Four methodology studies were found. There is substantial literature on improving LCA methods. The search criteria that were used aimed to find papers that specifically involved one or more LCA studies and their details. The papers in this category did conduct an LCA study, but the purpose was to test proposed methods.

3.2.3 Observations

LCA Methods allow for the modeling of different types of agricultural systems (albeit mostly large-scale conventional farms and some organic farms). Some methods, such as EIOLCA, have been developed to try to reduce the overhead inherent in LCA, by allowing analysts to calculate estimates. However, the process is very involved, requires expertise in the method, and it is difficult to reuse models, thereby taking advantage of effort already expended. In general, accurate, thorough, and rigorous LCAs are effort-intensive.

Each of the LCA studies presented in this chapter provide further insight into how the LCA technique is customized for and commonly used in the assessment of agricultural systems, such as the creation of hybrid LCA methods and streamline LCAs. In this section, I articulate these findings as seven observations regarding LCA for agriculture.

3.2.3.1 Observation 1: The scope of an Agricultural LCA is often Cradle-to-Gate

The most common type of LCA used in the analysis of agricultural systems is a cradle-to-gate analysis, since once the product is ready for shipping, the storage, variety of packaging, distribution methods, preparation, and consumption, among others, vary widely. Table 3 lists the LCA types used in the representative sample of LCA studies, highlighting those that involved a cradle-to-gate LCA.

The scope and boundary of the cradle-to-gate agricultural system LCAs are very similar to each other. The final product of the agricultural system is usually some form of raw product, such as a meat, grain, fruit or vegetable. The amount of processing this food product undergoes within the system of interest also varies widely in some cases, the final product is frozen [146], ground [54], deboned [167, 171], packaged [92, 187], or transformed into some derivative transportable product such as sugars from sugarcane [183].

Table 3.3: Functional units in agricultural LCAs.

Location (s)	**Product (s)**	**LCA Type**	**Functional Unit**	**Ref**
Canada	Beef	Cradle-to-Gate	1 kg live-weight beef	[21]
USA	Beef	Cradle-to-Gate	1 kg HSCW*	[167]
Australia	Corn	Cradle-to-Grave	1 kg of corn chips, Box of 10x400g corn chips	[92]
USA	Corn	Cradle-to-Gate	1 kg of dry biomass (dry grain or dry stover)	[121]
Netherlands	Milk	Cradle-to-Gate	1 kg of ECM**	[215]
Sweden	Milk	Cradle-to-Gate	1000 kg of ECM**	[39]

Continued on next page

Table 3.3 — continued from previous page

Location (s)	**Product (s)**	**LCA Type**	**Functional Unit**	**Ref**
USA	Milk	Cradle-to-Gate	1 kg of ECM**	[214]
Australia	Pork	Cradle-to-Gate	1 kg or 1 tonne HSCW*	[251]
France	Pork	Cradle-to-Gate	1 kg live-weight pork, 1 ha of land used	[19]
Sweden	Potato	Cradle-to-Retail	1 kg potatoes in 2kg paperbag	[187]
Germany	Sugar beet	Cradle-to-Harvest	1 tonne of extractable sugar	[30]
UK, Germany	Sugar beet	Cradle-to-Gate	50 000 kg of fresh weight sugar beet	[22]
Switzerland	Wheat	Cradle-to-Gate	1 ha, 1 tonne of grain, 1 tonne of grain with constant quality (i.e., 13% protein)	[46]
USA	Wheat	Cradle-to-Gate	1 kg of wheat grain	[173]
USA	Wheat	Streamlined hybrid EIOLCA	PLCA 0.67kg of wheat flour (approx. flour for 1kg loaf of bread)	[141]
Sweden	Beef, Milk	Cradle-to-Gate	1 kg bone-free beef, 1 kg ECM**	[40]
Australia	Beef, Mutton	Hybrid Input-Output Cradle-to-Gate	1 kg HSCW*	[171]
UK, Spain, Uganda, Kenya	Broccoli, Salad crops, Legumes	Cradle-to-Grave	1 ha of field, 1 tonne or 1 kg of produce, 1 kg of produce at home	[146]
Sweden, Malaysia, Brazil	Rapeseed, Oil palm, Soybean	Land use LCA	1 tonne of produce	[139]
Canada, Chile, Norway, UK	Salmon	Cradle-to-Gate	1 live-weight tonne of salmon	[168]
Argentina, Denmark	Soybean	Consequential LCA	1 kg of soybean meal produced in Argentina and delivered to Rotterdam Harbor	[54]

Continued on next page

Table 3.3 — continued from previous page

Location (s)	Product (s)	LCA Type	Functional Unit	Ref
UK, Australia, US	Sugar beet, Sugarcane, Corn	Cradle-to-Gate	1 kg of monosaccharide (glucose or fructose)	[183]
Australia	General	Hybrid EIOLCA	Whole Farm	[252]
Germany	General	Customized Process LCA	1 ha of farmed grassland, 1kg of milk, Whole Farm	[97]
USA	General	Cradle-to-Grave Sustainability LCA	No singly unifying unit. Closest: $, “unit” of energy.	[102]

*HSCW = Hot Standard Carcass Weight

** ECM = Energy Corrected Milk

kg = kilogram, ha = hectare

3.2.3.2 Observation 2: The unit of analysis of agricultural systems is often either Land Used or Produce Weight

Table 3 overviews the functional units that are used in each LCA study. For instance, “1 ha of land used” is a popular metric [19, 146, 97], which allows for the calculation of energy intensity with respect to land use, demonstrating how much strain the system puts on the land. For single product systems, a functional unit is often in terms of produce weight, as it allows for the calculation of energy, emissions or impacts per unit weight of the product at the gate.

The decision of where the *gate* lies depends the system boundary, i.e., which of these processing techniques occurs on the farm. For example, in beef production, the farm-gate may be pre-slaughter or post-slaughter. This also determines the functional unit: for pre-slaughter the functional unit would be live-weight [168], while post-slaughter, a common unit is Hot Standard Carcass Weight (HSCW) [251, 171].

3.2.3.3 Observation 3: Granularity is non-negotiable

Sometimes, midpoint functional units are used to analyze system subcomponents or to allow for the discretization of processes. For example, in [251], HSCW (a pork industry supplier side standard functional unit), is used. It represents the end of the production process in the pork supply chain, i.e., the weight of the product at the slaughterhouse gate. This makes the unit incomparable to other pork or meat product LCA studies that may define the endpoint at the consumer side (the final product may be processed differently, e.g., bone out, lean meat, whole carcass) To address this issue, the analysts in the Australian Pork study also use two midpoint functional units: 1 live piglet and 1 live slaughter pig at the farm gate. These units allow the findings to be used in comparative studies. For reference, another pork production study, by Basset-Mens & Van der Werf [19], has a functional unit of 1kg of live slaughter pig as well, in addition to a land use unit (1 ha of land used).

However, not all LCA studies have a midpoint functional unit or a functional unit that can be used to compare the models produced in the study with other studies, even if they are ISO compliant. Functional units can also be highly specific to the system of interest, product, or location. For example, in [54], the functional unit is "1kg of soybean meal produced in Argentina and delivered to Rotterdam Harbor". The level of granularity is non-negotiable. While there must have been intermediate steps in the LCA that separated the different processes (e.g., just the transport component per unit weight from point A to point B), these numbers are not always released or easily accessible. Various levels of detail are lost to the reader, and more importantly the system cannot easily be broken down into reusable components. Unfortunately, while the functional unit is meant to make LCA studies more comparable and reusable, it is not always the case.

3.2.3.4 Observation 4: Flows are often compared across agricultural systems

Figure 3.4 and 3.5 (pages 46 and 46 respectively) show examples of flow diagrams for milk production from two different studies.

Figure 3.4 (page 46) is from a comparative LCA study that aims to highlight differences in the environmental impacts between organic and conventional dairy farming in Sweden [39]. The items in italics (fertilizers, pesticide, co-products from the sugar industry) are flow components that belong to the conventional farm, while the underlined items (peas) are only part of the organic farm. Figure 3.4 summarizes the boundaries, overlap, and primary components in the system of interest. During the LCI, both farms are initially treated as one large system of interest (hence one flow diagram) as the farms share certain sub-flows, and therefore certain inputs in common (e.g., concentrate feed). Thus, for the purpose of data collection, the analysts can simply gather a large inventory of resource flows, and later attribute them to the different processes within each farm system.

Similarly, Figure 3.5 (page 46) is from another comparative study of a conventional and organic dairy farm, this time in the Netherlands [215]. The authors also produce a set of inventory tables and flow diagrams similar to the Swedish study.

Even though the studies were conducted in different countries, there is significant overlap between the systems. The method of the breakdown, including the processes involved in milk production and certain types of inputs, are not only produced in a similar fashion, but may even be imported from the same source due to geographic proximity. Due to the way in which the data are presented, the lack of access to the actual life cycle inventory, and the lack of shared LCA models, doing a side-by-side comparison is difficult.

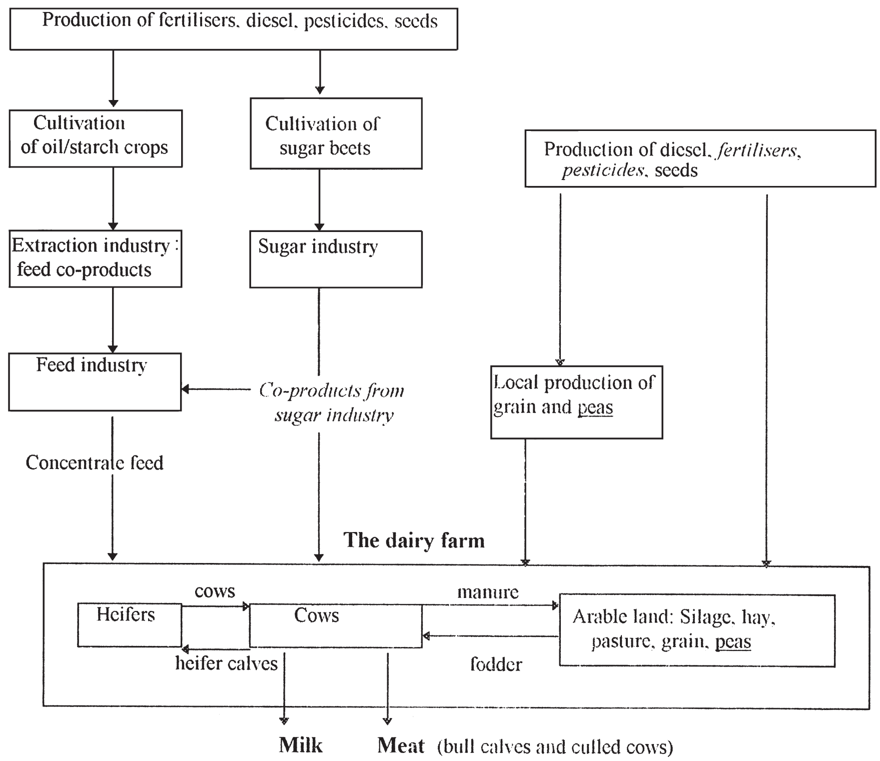

Figure 3.4: Flow diagram in Swedish study [39]: Underline = organic farm only, Italics = in conventional farm only.

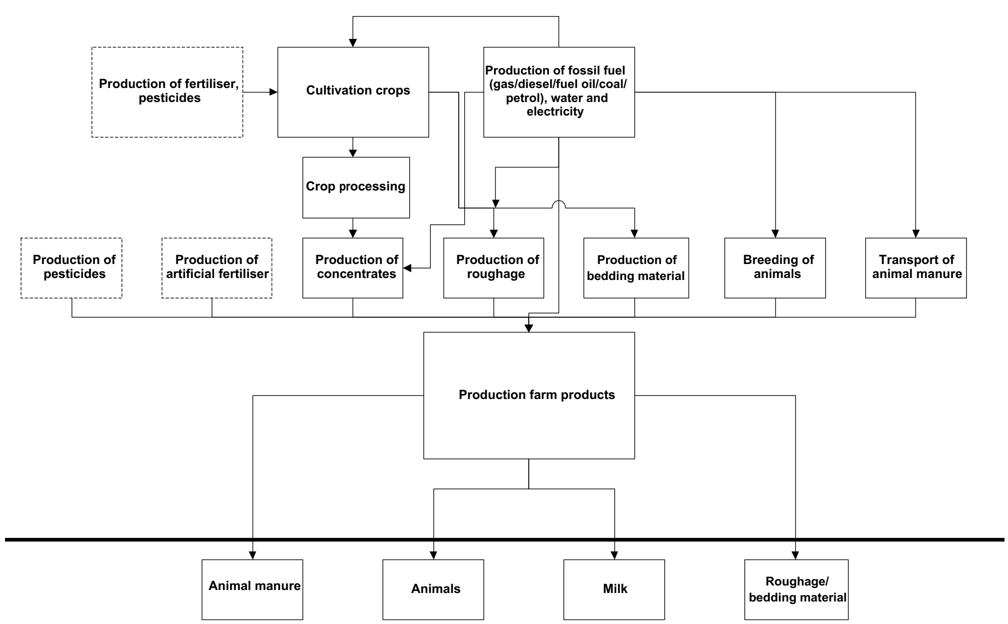

Figure 3.5: Flow diagram in Dutch study [215]: Dashed line = in conventional farm only.

3.2.3.5 Observation 5: Flows are often compared across agricultural systems in different regions

Pelletier et al. [168] conduct a comparative LCA of salmon farming systems in Norway, the United Kingdom, Canada, and Chile. While most of the previous work in LCA has focused on contrasting organic or alternative farming systems to conventional ones, there have many attempts at performing globally-scaled comparative assessments. The reason for these assessments is due to an increase in global supply food chains, the pervasiveness of environmental policies and initiatives across regions, and an interest passing environmentally friendly techniques across national boundaries.

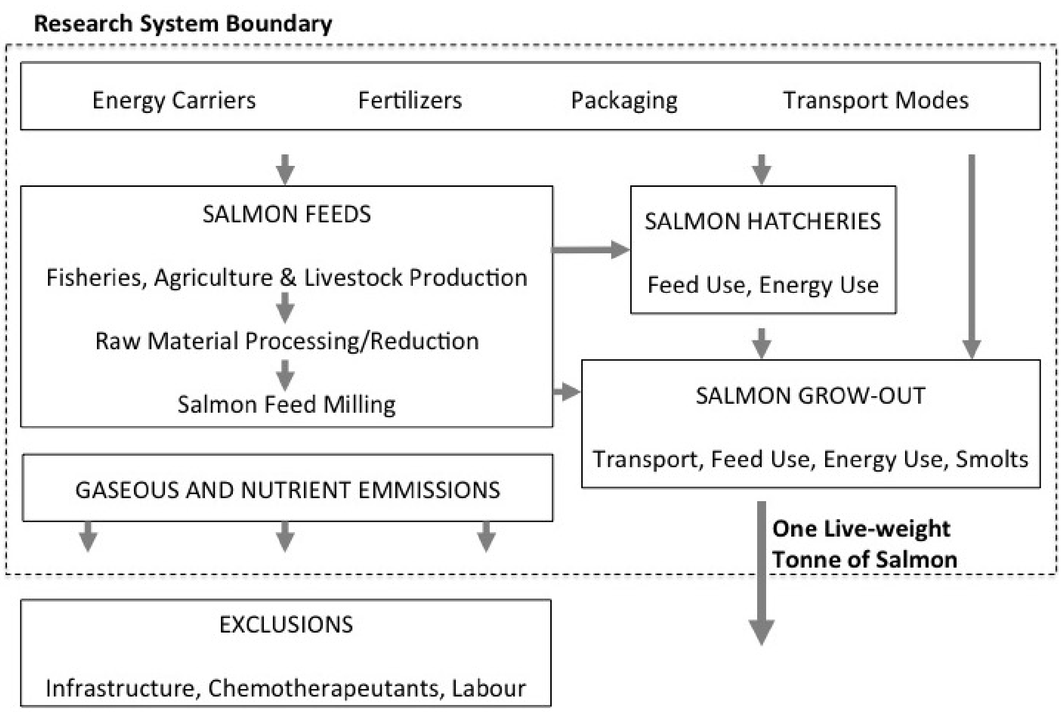

Figure 3.6: System boundary for the LCA of salmon production systems in Norway, the UK, Canada, and Chile. Redrawn from [168].

Figure 3.6 denotes the boundary and decomposition that is common to all four farms, even though they are geographically disparate. This means that even though the systems are seemingly different, by having a common functional unit (1 live-weight ton of salmon), and the same LCI method, a comparative analysis can be conducted. The data collected for the Energy Carriers, Fertilizers, Packaging, and Transport Modes in this study were derived from the same database, and were then modified for local conditions. Pelletier et al. demonstrate that, once a common method is used to model systems, the data compatibility issues are addressed and one is able to do comparative analysis effectively.

3.2.3.6 Observation 6: Flows are compared across product systems and regions

Renouf et al. perform a comparative assessment of the production of sugars for fermentation in Australia, corn production in the US, and sugar beets in the UK [183]. The product of interest was a sugar suitable for fermentation, as its bio-products have wide use, including as an alternative energy source. Here, in addition to systems based in different locations, the initial crop is different too. The functional unit in this study is 1 kg of monosaccharide (glucose or fructose), as this enables comparability across sugarcane, corn and sugar beets. As opposed to conducting a separate LCA study based on the specific sugarcane farms, the researchers used data from a variety of Australian inventory databases, local survey data, and other academic publications that have looked at different processes within the sugarcane production system (data sources are detailed in the paper). Similarly, for the U.S. corn [121], and the British sugar beet [217] impact numbers, the researchers looked at two sets of studies for each case, and converted their functional units (hectares of land) into 1 kg of monosaccharide, based on the yield numbers reported. As all the U.S. corn and British sugar beet studies had a high level of detail available in the report, the resulting analysis is precise comparison between the three sugar production systems.

Renouf et al. demonstrate three issues in the study:

1. Conducting a geographically diverse comparative LCA study is an involved process requiring compatibility of data from various regional sources.

2. Comparing different agricultural systems, even when the final product is similar or equivalent, is a difficult process that requires standardized methods.

3. Analyzing diverse environmental models (the report was a result of a multi-phase, multi-year project) is a tedious process due to the various conversion issues at play.

This study also resulted in the contribution of data to the Australian Life Cycle Inventory Database initiative. Similar initiatives exist across the world, focusing on the development and maintenance of third party databases containing Life Cycle Inventory data. Many of these databases rely on the collection and sharing of data that result from LCA studies such as that by Renouf et al.

3.2.3.7 Observations 7: Flows are connected and compared across entire sectors in the algriculture industry

Heller et al. [102] perform a very broad review of the United States food system by using a life cycle perspective to connect systems within different sectors of the industry. They use a product life cycle approach to analyze sustainability indicators (economic, social, and environmental) across different life cycle stages: resource origin, growing and production, food processing, packaging, and distribution, preparation and consumption, and end of life management. This study is unique in that it attempts to address the entire US food system, connecting different agricultural systems without resorting to a sector based approach like EIO-LCA [104]. Heller et al. did not conduct a new LCA, instead opting to review LCAs in published literature and connect information about the impacts that occurred at each stage to provide a holistic view of the food system. It is still one of a small number of papers that attempts to connect impacts across products and agricultural sectors over a large region, thereby encompassing a sizable portion of the industry.

Another massively-scaled LCA study is available in a report by the Center for Environmental Strategy at the University of Surrey by Mila i Canals et al. [146]. The paper details a series of comparative LCAs, which combined aim to compare the environmental impacts of domestic versus imported vegetables. They compared broccoli production in the United Kingdom and Spain, salad (lettuce) in the UK, Spain, and Uganda, and finally, legume (green bean) production in the UK, Uganda, and Kenya. The life cycle of each product is geographically disparate, therefore they break it down into three projects/reports chunked as follows: "cradle-to-central-depot" [146], "retail-to-plate" [147], and "consumption-to-waste" [153], The report highlights the importance of connecting LCAs across products, production systems, regions, up to connecting the entire industry. It is because of this highly detailed, connected set of LCA models that they can come to the surprising conclusion that local is not always more environmentally friendly. Indeed, the analysis reveals that:

> *"Working with 'food miles' as an indicator of environmental impacts for food products is potentially misleading: imported produce may have lower environmental impacts than domestic produces supplied off-season through increased storage and/or produced using enabling technologies such as heated and lit greenhouses."* [146]

3.3 Data and Tools for LCA in Agriculture

Conducting a life cycle assessment of a system to investigate and quantify environmental impacts is a modeling process. In particular, LCA models of agricultural systems are good prototypes to study as they represent complex phenomena and data. Many tools have been developed to assist in all aspects of LCA, from the inventorying process, the impact assessment, to eventual reporting of results. This section provides a brief overview of the state of the art in the LCA modeling process, databases, and software.

3.3.1 LCA models

The LCA modeling process results in models that are represented linguistically (e.g., interpretation), mathematically (e.g., LCIA results), and in static diagrams (e.g., flow diagram, LCA model). These form a document chain similar to that found in the software modeling process (see Figure 3.7, page 51). This chain is not strict, in that the LCI and the LCA model can also be thought of as descriptive models with more details captured of the system of interest. In addition, not all of these artifacts are necessarily models.

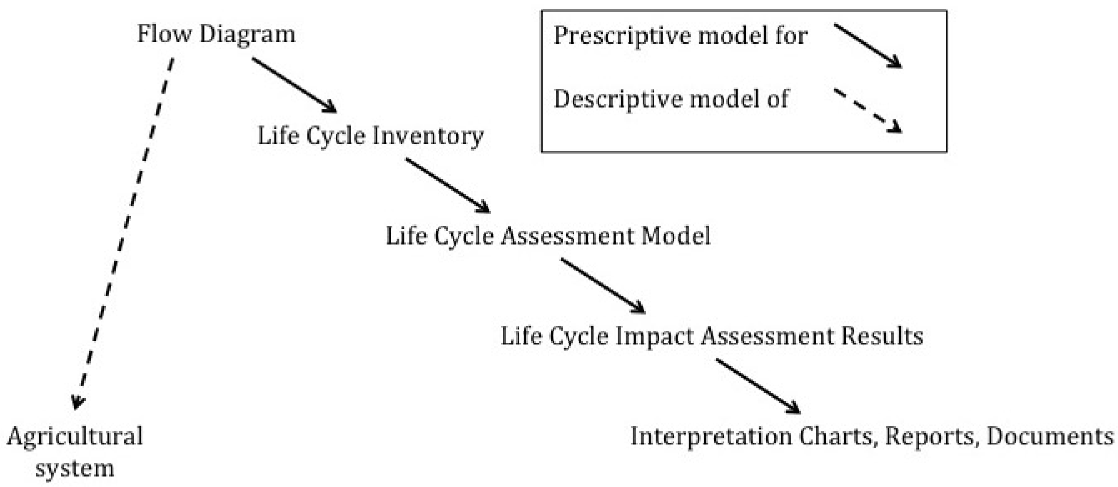

Figure 3.7: The LCA modeling document chain (modification of [135]).

Ludewig [135][1] describes three criteria for an artifact to be considered a model, which reflect how relevant attributes are mapped from the real world into a model:

1. Mapping criterion: Is there an real object or phenomenon the model is mapped from?

2. Reduction criterion: Are only the relevant attributes captured in the model?

3. Pragmatic criterion: Is the model useful for some purpose?

[1]These criteria are in fact based on Ludewig's translation and intepretation of Stachowiak's German text "Allgemeine Modell theorie", published in 1973 by Springer-Verlag, Wien

Each of the LCA artifacts described can be considered as a model. The first three (Flow diagram, LCI, and LCA model) are common to all LCA studies. The LCIA used and the Interpretations vary widely. In some sense, the first three are part of the model creation process, while the last two are analysis and interpretation models. Let us briefly consider how each LCA artifact adheres to this model criteria.

1. Flow diagram —

   Mapping: Maps major subcomponents in an agricultural system.

   Reduction: Only captures major resource consuming or producing components.

   Pragmatics: Provides a high-level system overview.

2. Life Cycle Inventory —

   Mapping: Maps major subsystems into individual unit processes.

   Reduction: Only captures data pertaining to environmental impacts.

   Pragmatics: Provides an inventory of flows and associated system impacts.

3. LCA model —

   *Mapping:*Maps environmental impacts to unit processes, creates unifying view of original agricultural systems.

   Reduction: Captures system attributes relevant to LCA in a whole system model.

   Pragmatics: Provides an overview diagram connecting the entire unit processes listed in the LCI.

4. Life Cycle Impact Assessments —

   Mapping: Mathematical model calculates whole system environmental impacts.

   Reduction: Mathematical model abstracts unit processes as system impact values.

Pragmatics: Provides whole system environmental impacts.

5. Interpretation Charts, Reports, and Documents —

   Mapping: Maps LCIA results into diagrams or written interpretations.

   Reduction: Each chart, report or document captures a subset of the LCIA results.

   Pragmatics: Provides LICA results in a meaningful manner for system understanding.

The LCA modeling workflow can therefore be scoped to begin with the flow diagram creation and end once the LCA model has been created. Figure 3.8 (page 54) summarizes how an LCA model is created. Three LCA models are produced: the flow diagram, the LCI (inventory of unit process), and the LCA model, in steps 1, 2, and 3 respectively, as labeled in this figure. The LCI databases used to populate the LCI, and popular LCA tools used to manage the LCA modeling workflow are described briefly later in this section.

Step 1: Create a flow diagram to represent the high level processes within the system of interest (such as Figure 3.4 and Figure 3.5). The flow diagram is the first model created in an LCA study. A flow diagram has three goals:

1. To represent the high-level system components.
2. To represent major flows of resources within the system of interest.
3. To demarcate system boundaries.

The flow diagram is modeled informally using simple box and arrow notation to represent the components and their relationships. No specific software tool is used to create flow diagrams: they range from back-of-the-napkin pen drawings to images created in a drawing tool (such as those included in the Microsoft Office suite [145]).

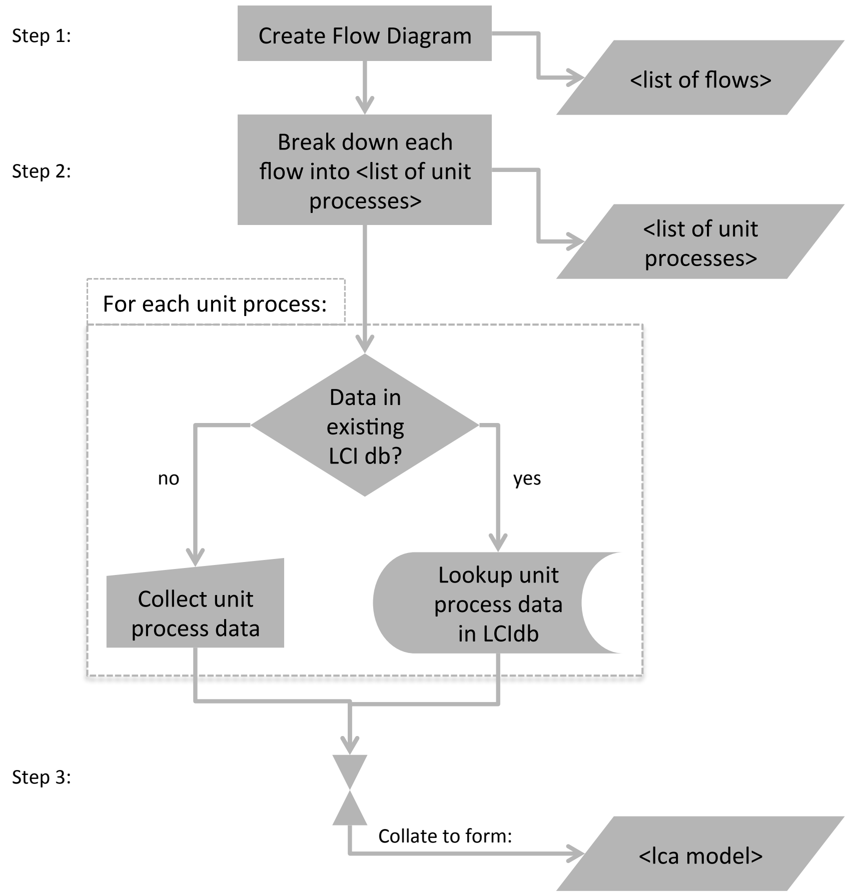

Figure 3.8: LCA modeling workflow.

Step 2: Break down the flow diagram into unit processes to represent the most basic flows in the system. Collect the appropriate data for each unit process (inputs, outputs, associated environmental impacts) either via primary data collection, lookup in published literature, or lookup in an LCI database. Model this unit process data using a data documentation format if it has not already been done.

Step 3: Collate the list of unit process data into an LCA model. It contains every unit process for every flow in the system relevant to the analysis being conducted. Connect all unit process data of a system in a coherent and complete LCA model using an LCA software tool.

3.3.2 LCA Data Documentation Formats

Each high-level component that was modeled in the flow diagram is broken down into unit processes that represent all flows of within the system of interest. These are aggregated and stored as a list of processes, known as the LCI.

A variety of LCI databases contain unit process data for a variety of flows ranging from extraction of raw materials, transformation of one product to another, use of specific materials, etc. Data Documentation Formats (DDF) are used to structure unit process data in these LCI databases and therefore also in the LCI of a particular study. The two major DDFs used in LCA are: ecoSpold [63], and the International Reference Life Cycle Data (ILCD) System format [65]. Both formats are open source and comply with the ISO/TS 14048 standard: "Environmental management — Life cycle assessment — Data documentation format" [113].

However, there are several issues using DDFs to standardize LCA data. Cooper & Kahn note:

> *"Although the resulting datasets, formatted in ecospold v1-v2 and ILCD, are intended to be ready for use in LCA software, extensive use of parameterization as well as improved meta data (e.g., data quality and uncertainty information) simultaneously present compatibility issues and opportunities for additional capabilities."* [52]

They are both based on XML and similar technologies (XLS, XLST, Schema), and in that sense can be thought of as LCI data markup languages. In particular, they are available as a collection of XML Schema Definition Language (XSD) documents. XSD is a language that is used to validate and model XML data [248]. The data documentation formats describe how the unit process will be modeled, including the nomenclature to be used and the relationships between the model components. They are used to standardize LCI data such that unit process data collected during different LCAs and related studies can be compiled into an LCI database.

As both ecoSpold and ILCD are very similar, only ecoSpold will be described. The ecoSpold format was first released in 2003, by the Swiss Center for Life Cycle Inventories (developers of the ecoinvent tool). It has since undergone many community driven improvements: ecoSpold format v2 was released after a revision process conducted by an ad hoc expert-working group [152] in 2007. While it is specifically designed for use with the ecoinvent database, the DDF itself can and is used by other LCI databases to structure their data (such as the USLCI database [157]).

ecoSpold models a unit process as an activity: "an independent process or activity that transforms a given input into an output of products or services" [63]. Figure 3.9 represents the ideal structure that all ecoSpold data should be modeled after. Elementary exchanges represent flows of raw/naturally occurring materials of the earth into the system. Intermediate exchanges refer to manufactured products, where the technosphere refers to industrial systems. The full vocabulary and structure of ecoSpold is available online [62]. The reference product is the intended output of the activity. The ecoSpold DDF uses a collection of XSD documents to prescribe the structure of unit process data to try to meet this underlying idealized model.

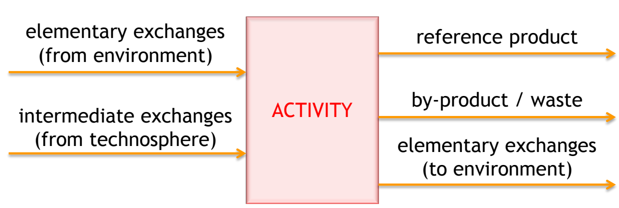

Figure 3.9: The ideal unit process data model as specified by ecoSpold [63].

DDFs and standards support data exchange between tools, reuse at the unit process level, and consistency across LCI databases. The continuous development of open DDFs like ecoSpold and ILCD means that the standard for formatting unit processes is clear and well documented. However, current DDF and LCA standards deal with two extremes of LCA: the DDF only addresses the structure of the unit process, and LCA standards only deal with the high level structure of an LCA study (the modeling workflow).

3.3.3 LCA Databases

Once a flow diagram has been created, and the analysts have a feel for how resources move within the system, they gather all the data required to calculate different environmental impacts. This process involves decomposing the high level steps in the flow diagram into individual sub-flows or processes. The basic unit of LCI data that is collected is the "unit process", defined by ISO 14044 as: "the smallest element considered in the life cycle inventory analysis for which input and output data are quantified" [112].

For each unit process, inputs and outputs (products, materials, and energy), and the associated environmental impact with it are listed. The question to be answered is: how does actually performing this step affect the environment? The data may be collected in several ways: primary data collection (via measurements or sample in the field), data obtained from published literature (e.g., academic papers, government reports, industry reports), data obtained from the results of simulations of approximately similar systems, or through lookup in a Life Cycle Inventory (LCI) database.

Due to the scope of the LCA, the number and size of the agricultural systems under study, the type and level of detail of the LCA to be conducted, and the availability of existing data, the LCI phase can consume the most time, money, and effort. LCI databases are built to support the data overload that occurs during the inventorying process. They contain structured collections of objects representing unit process data. An overview of some LCI databases used in Agricultural LCAs is available in Table 3.4 (page 58).

Table 3.4: LCI databases.

Name	Description	Ref
Regional Databases		
United States LCI db	Provides data for "material and energy flows into an out of the environment that are associate with producing a material, component, or assemble in the U.S."	[157]
European Reference LC db	Provides data "from front-running EU-level business associations and other sources for key materials, energy carriers, transport, and waste management"	[66]
Australian National LCI db	Provides "environmental information on a wide range of Australian products and services over their entire life cycle"	[209]
Specialized Public Databases		
Economic Input-Output LCA db	Developed by the Green Design Institute at Carnegie Mellon University for the EIOLCA method: "a mathematically defined procedure using economic and environmental data to determine the effect of changing the output of a single sector"	[36]
LCA Food db	Provides "LCA data on basic food products produced and consumed in Denmark". The data are compiled from research papers and case studies conducted by researchers and analysts from 2-0 LCA Consultants, and members of the Faculty of Agricultural Sciences at Aarhus University.	[159]
World Food LCA db	Developed by Quantis, with industrial food partners (including Monsanto, Nestle, and Kraft Foods) to create a global LCI db with data on agricultural production, and food and beverage processing. Preliminary notes were published the 9th International LCA of Food conference, with a final update coming in 2015.	[126]
Proprietary Databases		
ecoinvent	LCI data from partner research institutes and LCA consultants are compiled by the Swiss Centre for Life cycle Inventories. They also invite practitioners to submit their datasets.	[62]

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Table 3.4 — continued from previous page

Name	Description	Ref
GaBi db	LCI data are based on PE International's consulting work with different system owners, industry groups, and public bodies.	[212]
SimaPro db	LCI data are based on Pre International's consulting work. They also have a subset of data specifically on agricultural systems, available as the "agri-footprint" database [3]	[195]

Within the LCA studies surveyed in this chapter, the national or regional LCI databases that analysts interact with are: the United States Life Cycle Inventory (USLCI) database [157], the Australian National Life Cycle Inventory (AusLCI) database [209], and the European Life Cycle Database (ELCD) [66]. Additional databases are listed in Table 3.4. Although this list is not exhaustive, others exist, many of which contain smaller, specialized datasets.

Many proprietary databases are populated via primary data collection performed by consultants in partner organizations. These proprietary databases often aggregate existing free databases, and/or resell other proprietary databases as part of a package deal. ecoinvent [62] is such an example, and is popularly used to supplement data regarding machinery, infrastructure, or capital goods in an agricultural LCA. These data are often international in scope. Most databases (with the exception of the EIOLCA tool [36]), contain data gathered during process-based LCAs. Some new database initiatives focus specifically on agricultural and food systems, some of which are also included in Table 3.4.

Some databases, such as USLCI and ecoinvent, only release data in the ecoSpold format, ELCD and GaBI only use ILCD. Whereas others, such as AusLCI,, have versions of their data in both formats. A substantial effort is being made to connect LCI data across databases. To this end, both ecoSpold and ILCD aim to support "alternative modeling options and data exchange [with each other]" [152]. The data from LCI databases are usually exported as collections of either XML (a portable data format) or XLS files (used by Microsoft Excel [143] and other spreadsheet software packages). Collections of XML data are used in most major LCA software tools, as will be discussed next.

Many of the databases described in Table 3.4 have been created and modified to include LCI data for a larger variety of systems types: i.e. not just industrial production systems. The World Food LCA database focusses specifically on LCI data for agricultural production and processing and is intended asan open data project. Government-run LCI databases like the USLCI, ELCI, and the AusLCI also aim to incorporate more LCI data relevant to agricultural systems. The combination of data collection for agricultural LCI databases, and the continuous development of LCA tools means that the LCA methods as they currently stand are being incrementally improved and better supported. Still, there is a lack of domain-specific LCI data, particularly for alternative agricultural systems.

3.3.4 LCA Software

Four of the most popular tools that are used throughout all the LCA phases are spreadsheet tools (due to its popularity, Microsoft Excel was chosen to represent spreadsheet tools), SimaPro, GaBi Software, and openLCA. Table 3.5 describes the basic properties and features of these software tools. The main differences between LCA software tools include modeling process, range of databases available, usability, data documentation formats, and cost [105].

Spreadsheet tools are a natural fit for the data-intensive [190] LCA process. They have the capability to create inventories easily, perform impact calculations on raw data, and produce charts exportable to partner word processing software for reports. Not only can most LCI data be exported as XLS/XLST, but many plugins, templates, and guides on how to use Microsoft Excel to conduct LCAs are available. An example of a spreadsheet tool is the Athena EcoCalculator, a template that allows for getting snapshots of the environmental footprints of buildings [15].

Pre International develops SimaPro (in addition to their own LCI databases) [194], one of the most popular full stack proprietary LCA software tools. In direct competition is GaBi Software, a "product sustainability performance solution", developed by PE International [213], that is also used to conduct LCAs (they too have their own LCI database). Both GaBi and SimaPro have a similar set of functionality, and are industry leaders. They are expensive, but have alternative limited access licenses for education and teaching. Many other proprietary LCA tools of varying complexity and capacities exist. These include: Sustainable Minds [206], Umberto NXT LCA [109], Quantis Suite [178], among others.

openLCA is one of the few free and open source tools aimed at professional LCA and footprint analysts [94]. GreenDelta, an environmental consulting group based in Germany, conducts core development for this tool. In addition to having LCIA capabilities with built-in methods, data connectivity with popular LCI data documentation formats, and reporting functionality, openLCA also allows for users to build their own plugins to extend it. GreenDelta is also responsible for the openLCA Nexus website, which aggregates LCI data from different databases and allows for them to be searchable in one interface (Note though, that many of these databases are proprietary and still require licenses [95]).

Modern LCA tools have provided some support for connecting to LCI databases, automated report production, basic versioning information to track changes, and simple localized user-created libraries for reuse within a project (e.g., a single user creates a set of models and can save parts of it for later use within the same instance of the tool). The openLCA project fills the need for open source tools for the LCA community. Development on each of these LCA modeling tools is ongoing with new and promising features being rolled out each year. while there is interest in bridging the gap between the need for domain-specific data, these tools are still designed for the domain-agnostic LCA modeling process.

A comparison of these four LCA tools in summarized in Table 3.5 (page 62).

Table 3.5: Summary of LCA software.

Product Details				
LCA Tool	**Excel**	**simaPro**	**GaBi**	**openLCA**
Developer	Microsoft	Pre Intl.	PE Intl.	GreenDelta
Current Version	Office 2013	v8, 2013	v6.3, 2012	v1.4, 2014
Release Year	1993	1990	1991	2006
License	Proprietary	Proprietary	Proprietary	Open Source
Platforms	W, O	W	W	W, O, L
File Format	X, C	X, C, S	X, C, G	X, C, S, O
W = Windows, O = OSX, L = Linux				
X = XLS/T, C = CSV, S = SimaPro, G = GABI, O = olca				
Data Documentation Formats supported				
LCA Tool	**Excel**	**simaPro**	**GaBi**	**openLCA**
XML	✓	✓	✓	✓
ILCD	✗	✓	✓	✓
ecoSpold	✗	✗	✓	✓
LCA Features				
LCA Tool	**Excel**	**simaPro**	**GaBi**	**openLCA**
DDF converter?	✗	✓	✓	✓
Unit process groups?	✗	✓*	✓*	✗
LCI database?	✗**	✓	✓	✗**
LCIA methods?	✗**	✓	✓	✗**
General Features				
LCA Tool	**Excel**	**simaPro**	**GaBi**	**openLCA**
Reports?	✓	✓	✓	✓
Extensibility?	Macros	✗	✗	Plugins
Change tracking?	✓***	✗	✓***	✗****
*Unit processes can be grouped and saved locally only.				
** Needs to be imported.				
***Some historical information associated. In excel, all text is tracked, in GaBi, all objects.				
*** Version numbers only				

3.4 Scenario-based Analysis: Creating an LCA model

3.4.1 Methodological Note

The decomposition of an agricultural system into quantifiable unit processes, the assumed relationships between different data, and the means by which unit process data are brought together in a synergistic way in an LCA model to enable the calculation of the environmental impacts of the system of interest have been described previously. LCAs can be leveraged to do more than just retrospective evaluation, as described in Section 3.2. The current LCA modeling process can be scaffolded to enable more proactive evaluation, monitoring of systems, and to use LCA results as a decision making tool during the system design process.

In this section, I present a single scenario, concerning the creation of an LCA model, as it exemplifies the modeling process and challenges that would be faced by a small- to medium-scale sustainable farmer.

In fact, it is part of a larger analysis in which I developed a series of scenarios describing hypothetical modeling activities enacted by potential LCA stakeholders. The goal of the full set of scenarios was to tease apart the core issues with the LCA modeling workflow and the capacity of these existing LCA data structures and tools to connect and compare agricultural system.

Section 3.4.4 highlights the modeling challenges identified through the scenario presented in this chapter. The issues identified during the full scenario-based analysis, in concert with work presented in this chapter, are collectively discussed in Section 3.5.

3.4.2 Scenario Context

Scenario Goal: Demonstrate the modeling process of creating an LCA model for a small-scale alternative agricultural systems.

Consider the following hypothetical scenario: Alice Kidogo is the owner of a small urban farm growing an assortment of fruit and vegetables in Orange County. It is 2016, California is experiencing a drought, and she suspects that the state government will impose water rations.

She currently supplies produce to certain farm-to-table restaurants in the Orange County region. She would like to apply to be a supplier at the Whole Foods in her geographic area. She is aiming to score "Good" to "Better" on the Whole Foods Responsibly Grown ratings [250]. She wants to conduct some form of environmental assessment to help her meet these goals. Alice wants to be proactive and use this opportunity to also optimize her water usage and lower her water footprint.

As the farm is composed of many different subsystems, she wants a reasonably fine-grained assessment that allows her to: identify major water sinks, detect inefficient water flows, and understand the farm's overall relationship with water. Alice also wants to be aware of the effects of her water-saving choices with respect to other environmental issues. For example, one concern that she has is the relationship between the heavy use of plastics within her irrigation system and the farm's carbon footprint. She wants to consider alternatives to reduce her water footprint in case of rationing. She needs to find ways to improve her water footprint without compromising the farm's overall environmental performance.

Alice begins by performing a Google search with the phrase *water or carbon footprint calculator farm*. She finds two online tools: The Water Footprint Assessment Tool [249], and the AgroClimate carbon footprint tool [197]. They provide her with interesting information about her local watershed, and some geography based statistics regarding water use. Unfortunately, even after spending some time trying to model her farm using the tools, they only allow her to get a rough estimate of the water footprint. As she wants to use the results of the water footprint assessment to make decisions about how to reduce the water consumption of different systems on her farm, these online tools do not suffice.

She then browses through the United States Department of Agriculture website, to see if they have any recommendations on conducting an environmental assessment of her farm. The website lists "Quantification Tools" in the "Environmental Markets" section, including water quality, carbon and greenhouse gas emissions, and energy estimation tools [245]. Once again, they aim to provide a snapshot footprint of the environmental performance of the system. They are specifically geared toward enabling the farmer to participate in emerging environmental markets involving, for example, the trading of offsets.

Alice decides that a Life Cycle Assessment would provide her with a potential means to quantify and understand the environmental performance and of her farm. However, LCA seems to be a complex and time consuming venture, and Alice worries that she may have to resort to hiring professionals to provide her with the most reliable water footprint. One online guide to LCA [20] informs Alice that it could cost from $10,000 to $60,000 to outsource the LCA to a consulting company. Due to financial constraints, Alice chooses to try and conduct an LCA of her farm on her own.

3.4.3 Scenario Walkthrough

Alice begins by creating a flow diagram. Since no dedicated LCA flow diagramming tool is available, she uses Microsoft PowerPoint [144] to create a simple block and arrow diagram to represent the major systems in the farm: the irrigation system, solar power system, grey water reclamation system, vermicomposting boxes, the nursery, and the farm grow beds themselves. As no formal guidelines regarding flow diagramming are available, she simply connects these blocks with arrows to represent directionality and types of flows within the system.

The boundary of the system can be scope in many ways. For example, Alice chooses to include the build of the solar power system and the irrigation system, as she custom built many of the components. In contrast, her gray water reclamation and vermicomposting systems are direct from vendors. She creates an initial flow diagram, as shown in Figure 3.10.

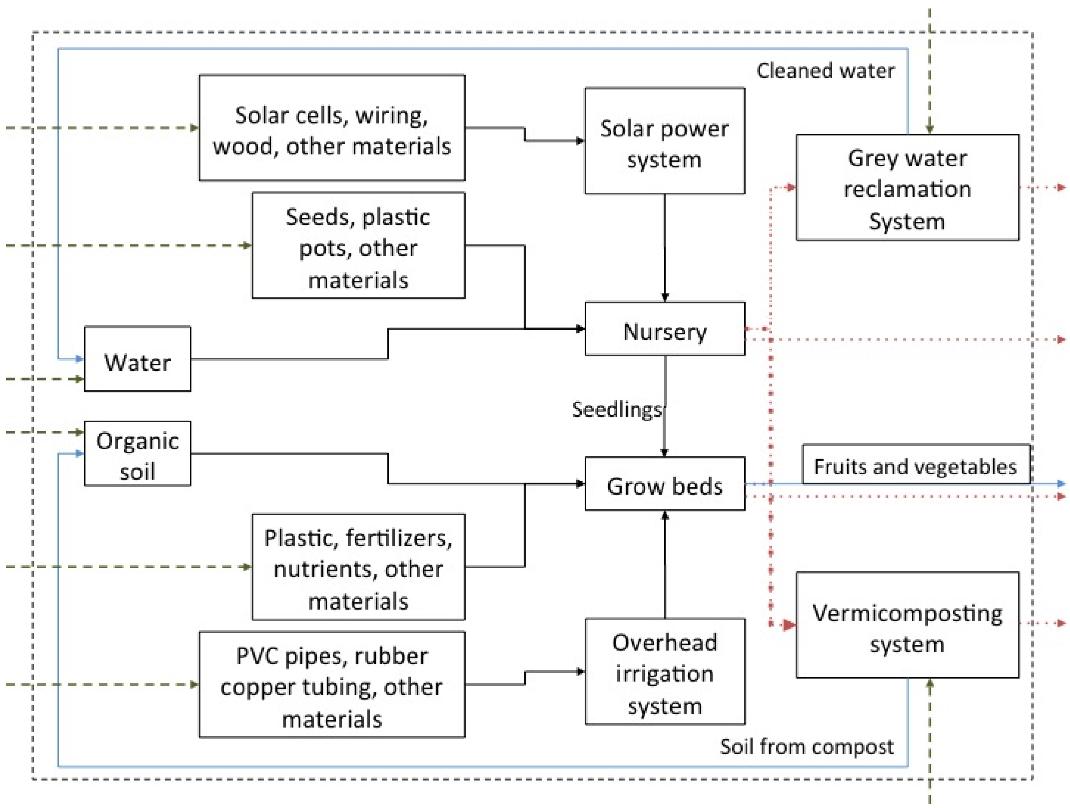


Figure 3.10: Alice's Farm: High level overview / preliminary flow diagram.

Alice goes through a variety of LCA educational materials, hoping to answer the following questions: how should she break down these subsystems, and what level of granularity is needed to calculate a useful water footprint? She converts her original flow diagram to the process based LCA flow diagram shown in Figure 3.11, created based on an introduction tutorial to LCA [13]. This represents her systems as a series of high-level processes: these would later be decomposed into unit processes, with relevant data potentially available in existing LCI databases.

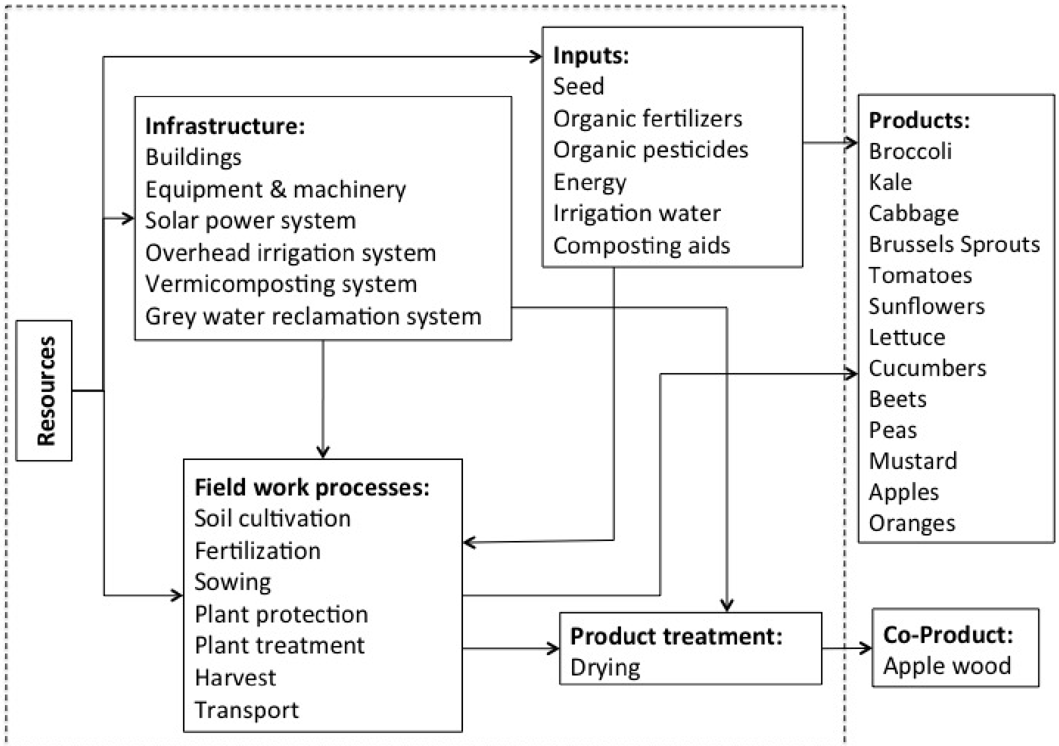


Figure 3.11: Alice's Farm: Final flow diagram.

No standard or generic LCA models are readily available to be explicitly built upon. Alice essentially begins from scratch when creating the LCA model, with minimal guidance on how to collect her data, what kinds of things to consider, and how to connect unit processes. Alice tries to create an LCI for just the irrigation system to try and see how far she can get.

She has two options, pull data from an LCI database, or manually collect the data required. Unit process data are contained in several LCI databases. Alice chooses to use the USLCI database, as it would likely contain a geographically appropriate dataset for her southern California based farm. She uses Microsoft Excel to create a basic LCI. She tries to source much of her equipment and materials used on the farm from local vendors, and hopes that relevant data will be available in the USLCI.

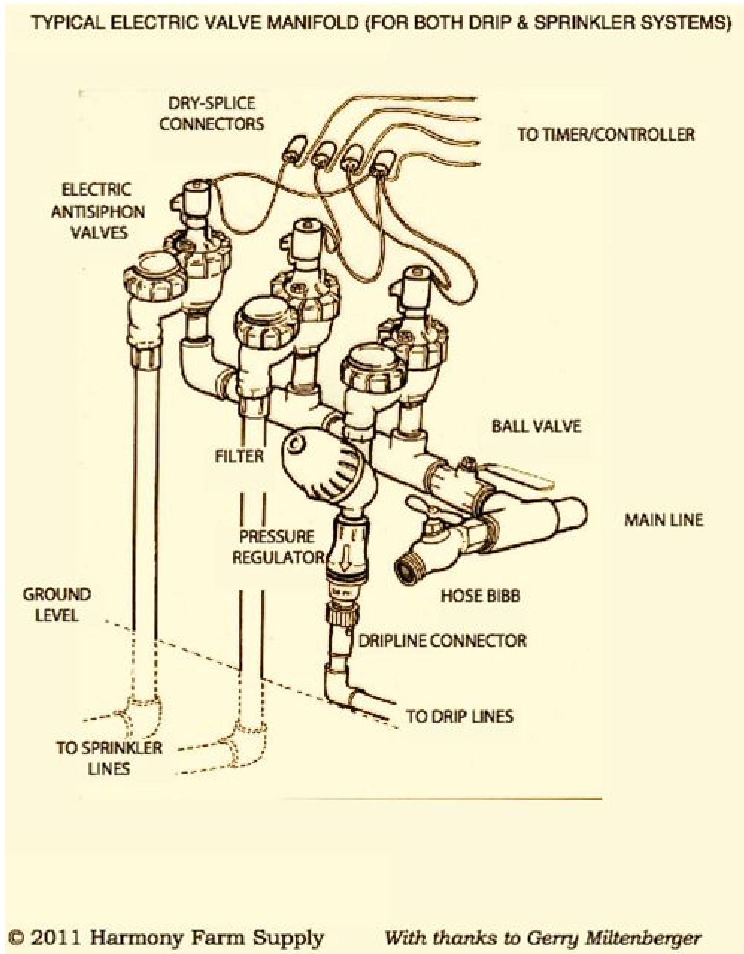


Figure 3.12: Irrigation system head, Harmony Farm Supply schematic diagram [99].

For example, the irrigation system on the farm is based on Harmony Farm Supply & Nursery's sprinkler irrigation setup. The most complex part of the system is the "system head or manifold assembly" [99]. It is responsible for distributing water among the main lines (in Alice's case, powered by the Solar power system on the farm), and shown in Figure 3.12. Each of the sprinkler lines would result in a network of yet more tubes, fittings, and other parts. A complete accounting would require the knowledge of the environmental impacts of each of these subcomponents of the irrigation system, and potentially even background information on their origins. Ideally, manufacturers of these parts would provide these data.

Alice looks up *irrigation* in the USLCI to see what kind of data is available. Figure 3.13 shows the list of data available to her. None of the available data is relevant to her specific setup. The publicly available USLCI appears to mainly contain data for large-scale industrial processes, and the farming data is therefore also of that scale. She does note that the USLCI has three phases of data under development: field crop production data, Irrigation, manure management, and farm equipment operation unit process data, and mineral, fertilizer, herbicide, insecticide, and fungicide data. However, these data are not available yet. The USDA crop LCI database contains some of these data, but as with the USLCI database, it is missing certain kinds of data relevant to her system.

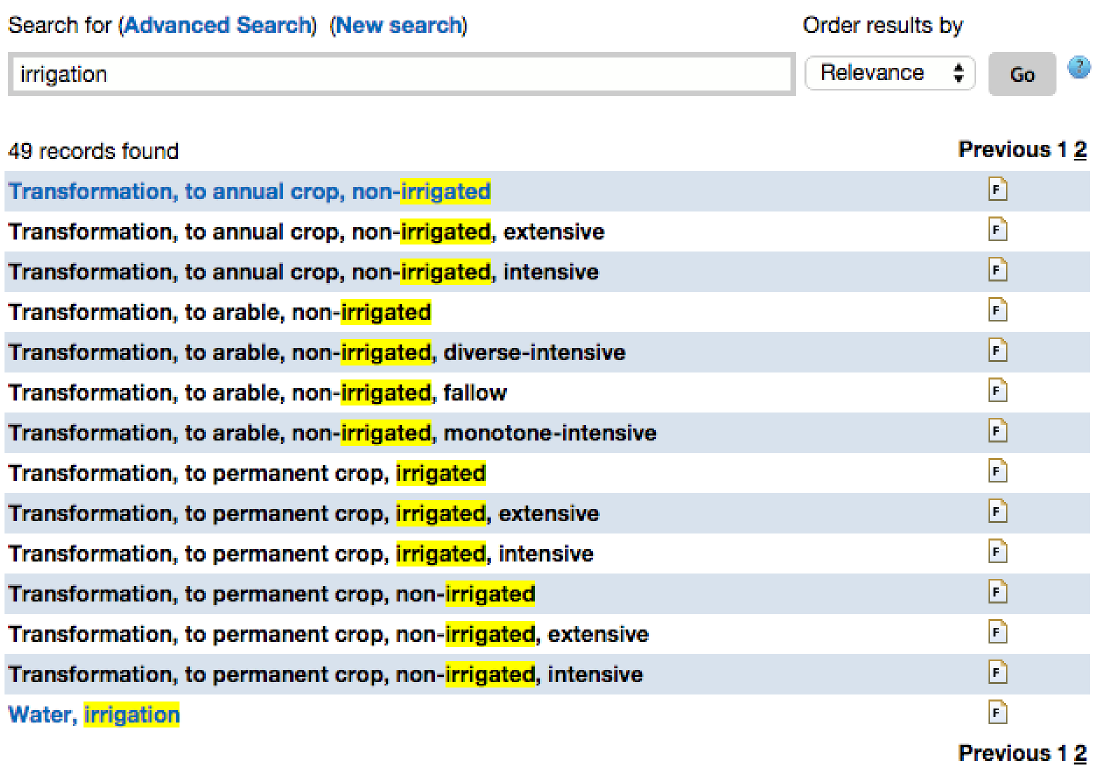


Figure 3.13: USLCI search for “irrigation” unit processes [157].

To continue with creating the LCI and the overall LCA process, Alice has the following options:

1. Manual data collection: Collect the necessary data, represent them as unit processes, and add them to her LCI.

2. Pay for the data: Alice could subscribe to an agriculture specific, private, and proprietary database. The Agri-Footprint database by SimaPro is only available if one has a service contract [3]. It is not clear, however, whether these data would be relevant to her alternative agricultural system.

3. Hire a consultant: Taking the problem out of her hands and placing it into those of a professional LCA expert would certainly get the results she wants, but comes at a steep price.

Alice chooses to continue conducting the LCA herself. She meticulously collects environmental impact data for each resource flowing in and out of her farm, entering each unit process into the spreadsheet based LCI. When she finally has a complete LCI for her farm, she looks for an LCA modeling tool that will allow her to create and connect each of the unit processes and create a coherent system model once again. For this step, Alice uses the free openLCA tool to connect each of the unit processes and create the LCA model representing the environmental impact of her agricultural system.

3.4.4 Modeling Challenges in Scenario

The scenario presented in this section demonstrates the inadequacy of LCA for the modeling of a small scale alternative agricultural system. Three modeling challenges are highlighted through this scenario.

One: Disconnected modeling process. As Alice moved through the modeling process, she used:

- Microsoft Powerpoint to create the flow diagram.
- Microsoft Excel to create the inventory
- USLCI and USDA external databases to look up unit process data
- openLCA to create the final LCA model

Each modeling step required a different tool. While this alone may not be problematic, the modeling effort put into one step is lost in the next. The largest gap is between flow diagram and inventory, as no current tooling can support the connection of the two. openLCA does have the capability to import an entire external LCI database, as well as spreadsheet based inventories. The inventories, however, must then be structured according to the formats usable by openLCA.

This modeling process also requires an abrupt switch from a very high level diagram — the flow diagram — to a detailed inventory requiring low-level information about her farm. There is no process connectivity between the two steps and information does not flow between the models.

Two: Time and effort overhead. Models must be manually inspected to ensure completeness and correctness. This may result in a suite of errors, such as models that misrepresent the system, models that are missing portions of the real world system, or models that have incorrect connections between processes. Further, the modeling effort expended to create the flow diagram is not utilized to reduce effort in the LCI creation process.

The majority of LCI databases are focused on industrial production systems. Those that are concerned with food are oriented toward the production of processed foods as a result of partnerships with food processing stakeholders. Data required to conduct an LCA of any alternative agricultural systems is unavailable and puts the onus on the system owner to collect primary data.

Three: Lack of flexibility. Only one type of granularity, the unit process, can be modeled. There is no support for creating logical groupings of unit processes in the form of components and no capacity to create hierarchies of such components. Alice is locked into two disconnected levels of abstraction: the high-level flow diagram, and the low-level inventory.

Even once an LCA model is created, current mechanisms only support the sharing of unit process data is shared. No other reusable portions of the model are explicitly supported. This also means that as things on the farm change, an entirely new LCA model would need to be created.

3.5 Essential Difficulties

Life cycle assessment (among other environmental impact assessment techniques) has enabled people to investigate, quantify, and understand the environmental impacts of agricultural and industrial systems. On the whole, LCA is useful, but it is not without its limitations. LCA requires meticulous and tedious data collection for every single process within a system. A good LCA is comprehensive and results in detailed models, however it can be a time-consuming and cost-prohibitive process, depending on the size, complexity, and novelty of the system under analysis.

The development of software also involves modeling, and there has been substantial research into improving the software modeling workflow. In the following analysis, I call on software engineering research and practice to tease apart some of the modeling challenges faced in modeling the environmental impacts of agricultural systems, as well as to propose opportunities for future work.

Fred Brooks [31] discriminates between essential difficulties with software — those relating to intrinsic characteristics — and the accidental difficulties — those relating to temporary or circumstantial characteristics. He goes on to state that to address accidental difficulties, one must promote incremental improvements, but to solve essential difficulties, one must promote revolutionary improvements.

The challenges faced in the modeling of the environmental impacts of agricultural systems involve addressing both the essential and accidental difficulties. LCA is one of many environmental impact assessment methods that aim to address these difficulties. LCA methods, tools, and data have undergone immense incremental improvements (particularly with respect to the representation and analysis of agricultural systems). However, several essential difficulties remain.

Essential difficulties faced when modeling the environmental impacts of agricultural systems involve the representation, or capture, of complexity, change, and context of such systems. Interestingly, some of these mirror the essential difficulties or characteristics of software as defined by Brooks: complexity, conformity, and changeability [31].

3.5.1 Capturing Complexity

> *"The complexity of software is an essential property, not an accidental one. Hence, descriptions of a software entity that abstract away its complexity often abstract away its essence. For three centuries, mathematics and the physical sciences made great strides by constructing simplified models of complex phenomena, deriving properties from the models, and verifying those properties by experiment.*

This paradigm worked because the complexities were not the essential properties of the phenomena. It does not work when the complexities are the essence."

— Fred Brooks, No Silver Bullet: Essence and Accident of Software Engineering [31].

One of the goals of environmental assessment is to enable the optimization of human made systems to have more positive interactions with the natural environment, while still providing for human needs. LCA aims to enable the modeling of complex systems to provide an understanding of the relationship between these systems and the natural environment. One mechanism involved in modeling is the decomposition of the system into attributes to be modeled. In LCA, the relevant attributes of systems include:

- Scope and boundaries of the system;
- Material and energy flows within the system;
- Distinct subsystems or logical groups of processes within the system;
- Dependencies or connections with external systems.

Only some of these attributes are represented in current LCA models: the flow diagram informally represents the scope and boundaries of the system and data documentation formats provide structure when representing unit processes. Dependencies, subsystems, and other potentially relevant attributes are linguistically represented, i.e., they are often described in reports that accompany LCA models.

Through the structuring of unit processes as prescribed by DDFs and the list-of-unit-processes LCI inventory, LCA results in a powerful declarative model: one where within the system boundary, unit processes represent all major flows of material and energy within the system, and are connected through the functional unit. One essentially ends up with a set of mathematical equations in the form of:

X units of each of [1:n] inputs produces a unit of some output

This allows the user to calculate the resulting environmental impacts by essentially solving for the amounts of waste, pollution, etc., produced per unit of final output (the functional unit reported in the studies as described in Table 3). This means of representing the relevant attributes is valuable for retrospectively calculating the environmental impacts of a system, however, these models have the power to provide more than just a footprint.

The capture of complexity is an essential difficulty inherent in the modeling of agricultural systems as:

- **Agricultural systems do not have a well-defined structure with clear-cut boundaries:** The modeling of agricultural systems is a squishy problem. For example: What is the appropriate *gate* in a cradle-to-gate LCA of a farm: is it immediately after harvest or after apples have been dried and turned into another product? Does one take into account the construction of the machinery used on the farm? How does one account for water lost from a system through evaporation: does that count as waste or use?
- **Agricultural systems are composed of subsystems:** A farm is not just a single process or always a single product system. Farms consist of networks of subsystems, many of which are commonly used. For example, all agricultural systems will have some type of irrigation system. However, it is only possible to represent an irrigation system as a group set of unit processes. LCA models are only reused at the unit process level, as it is the unit processes that are shared in LCI databases. The use of strict DDFs and the knowledge required of how various subsystems are constructed

and connected at the most basic level means that creating such models is a complex feat to achieve.

3.5.2 Capturing Change

"[E]conomics is very good at predicting when nothing changes, when trends continue, but it is not good at predicting changes in direction or turning points"

— R.C. Young et. al., Entrepreneurship, Private and Public [254].

Current LCA modeling is similar, in that it is effective at retroactively assessing static systems. Agricultural systems have a symbiotic (both mutualistically beneficial and parasitic) relationship with the environment, and are closely tied to the health of the environment due to the interconnectedness with many natural systems. These assessment of agricultural systems is unique (particularly in comparison to industrial production systems) as not only is one assessing a system that is directly dependent on the natural environment, but that also has a large component of it that are not of human construction, i.e., they are a part of nature: plants, animals, and the land. The quality of the food produced on a farm is related to the quality of the land, air, and water used. These are seasonal systems that are constantly producing, consuming, and evolving over time. The global warming potential of a farm in Northern California over the Spring of 2014, when they were growing peas and corn, will not be the same five years from now. For this reason, LCA models are time, location, and system sensitive. Dynamic models of agricultural systems that represent changing resource flows, however, are not available in the LCA modeling paradigm to date.

Existing LCA models and tools do not capture change effectively. They provide functionality to increment a model version number, but updating and maintaining models to keep up with changes in the real world is difficult. Excel has the "track changes" functionality [143], which is a helpful collaboration aid that provides different authors with awareness of how a document is changing, but is not explicitly geared toward capturing changes in LCA models. GaBi does something similar. The tool logs all changes to each object at every save (see Figure 3.14). Once again, the goal is to keep track of which user changed the model to support collaboration and not necessarily to augment the capacity of the model to reflect changes in the world. openLCA simply provides a version number for each object in the file that can be incremented as changes are made.

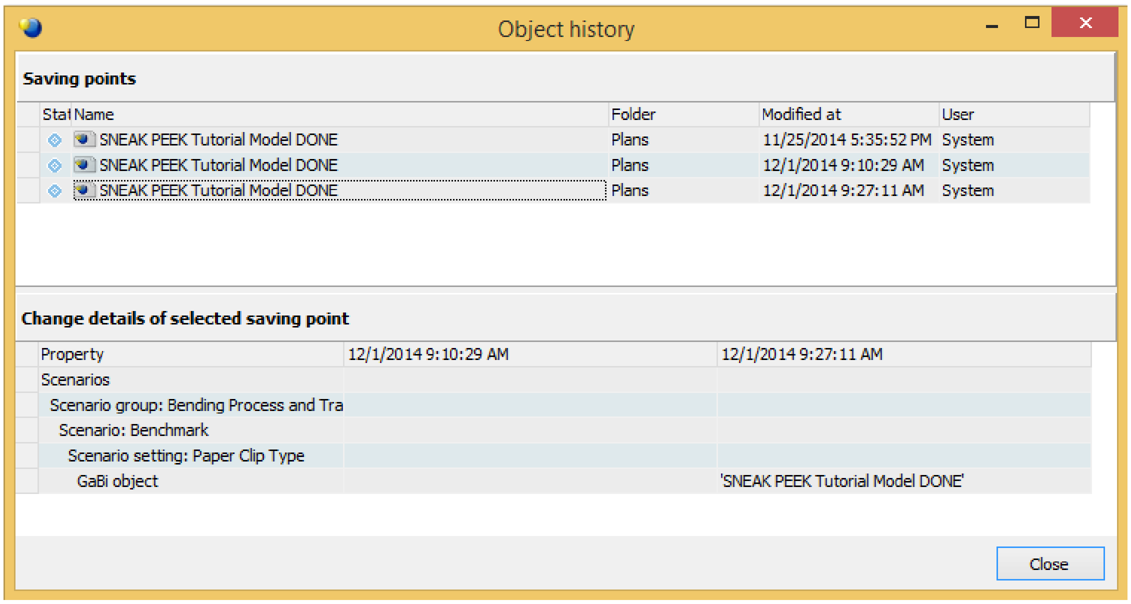


Figure 3.14: Sample object history: GaBi [213].

State of the art LCA modeling tools do not provide the ability to revert to previous models, compare models over time, or maintain a model history that reflects the changing world. If one is to update and maintain a model over time, it would involve a manual process of backing up and continuing from where one left off. While this is a valid approach, given the scale to which some LCA models can grow and the increasing complexity of agricultural systems, more advanced tool support is required.

The capture of change is an essential difficulty inherent in the modeling of agricultural systems as:

- **Agricultural systems are subject to human induced changes:** Agricultural systems change over time as people are continuously trying to improve the environmental performance of agriculture and to optimize them to meet growing and changing human needs. Any change, whether it is switching fertilizers, cultivation methods, or equipment used, has some effect on the environmental impacts of the system. If models are to provide useful assessments, then the lag with such changes needs to be minimal.
- **Agricultural systems naturally evolve and decay:** Finding mechanisms to represent the symbiotic relationship with the natural environment, and reflect changes in the world is difficult. There is a need to connect the trends and patterns observed in the natural environment to predict the natural evolution and decay of the agricultural system.

3.5.3 Capturing Context

> *"It is of the first moment to recognize that models do not exist in isolation and that, though they may at times be considered in their own terms, models are never fully understood except in relation to other members of the family to which they belong."*
>
> — Rutherford Aris, Mathematical Modeling Techniques [14].

We are constantly producing and trying to connect different types of information in the real world, as well as in our models. A model has two aspects: the representation of a system, and perspective on the system [202, 14]. When these models are treated in isolation, they provide representation without context. Such models cannot be connected with each other to produce meta-models, nor can existing models be reused.

When a model is created of an agricultural system, an artificially created system boundary sharply closes off the rest of the world from the system under analysis. The flow diagram tries to capture some contextual information by showing materials and energy flowing into and out of the system as a whole, but, as discussed earlier, the flow diagram is quite disconnected from the eventual LCA model. Trying to capture the context within which a system exists is a difficult problem. After all, one must scope a modeling problem appropriately lest they end up trying to simulate the world. The question remains, however, how does one capture the context of a system?

Standalone LCAs are still common as they are conducted when stakeholders of a particular system are interested in self-evaluation and improvement. Comparative LCAs are conducted when stakeholders in an industry are interested in pitting one set of production techniques against another, to analyze whether or not a new or alternative concept is actually better for the environment than an older or standard approach, or any of the other reason discussed previously in this paper. Conducting an LCA that is wide in scope is difficult, and so, when people are interested in understanding wider or more far reaching impacts, existing LCA studies are used to conduct retrospective meta-analyses. Environmental consulting agencies also tend to conduct these analyses, as part of their business model is LCA as a service (sometimes in addition to selling LCA modeling tools and access to proprietary databases), where they charge for their expertise, time, and effort. Depending on the intellectual property issues at play, they may own the model details and are not beholden to reveal the raw data to anyone else.

LCA models provide perspective on a specific system without any context. They are difficult to connect with each other to provide more holistic environmental impact assessments, and it is difficult to reuse partial models. People all over the world are producing extremely detailed models, with a lot of time, money, and effort going into inventorying complex systems. A vast amount of data and a large number of models are produced through LCA. We are unfortunately, producing, but not connecting, environmental impact models. No explicit interfaces or connectors are available to connect entire LCA models.

The capture of context is an essential difficulty inherent in the modeling of agricultural systems as:

- **Agricultural systems have complex resource flows both within and among systems:** Unit processes essentially represent the transformation and flows of resources. It represents the conversion of a set of inputs into a set of outputs. In the LCAs of agricultural systems, unit processes are used to represent the march of resources within a system, from the cradle to the gate, where the line begins with materials extracted from the earth, and ends with food, waste, and other by-products. However, many resources are flowing into and out of the system at different stages of production and from a myriad of external systems, not all of which can be captured in current LCA models

- **Agricultural system models are not shared or necessarily shareable:** The flow diagram discards the out-of-scope context, but there is still potential to connect it to the rest of the models. Just sharing unit processes is not enough, as they do not adequately capture contextual information. For example, if an organic soil producer made their entire LCA models, one might be able to understand how the use of that component, i.e., the organic soil, on one's farm, may affect other connected systems. However, issues revolving around the intellectual property or trade secrets involved in a production process may dissuade a vendor from sharing their models. This makes it difficult to compare models across product systems, geographic regions, and industries, to gain relative context.

Capturing contextual information and creating models with the capacity for connection is essential to providing a more holistic understanding of the environmental impacts of human made systems. By creating an ecosystem of models, available as open data, the reusability of such detailed models is increased, providing perspective on systems in context, and the potential for a deeper understanding of the sustainability of interconnected systems.

3.6 Implications for Design

LCA models are intended to provide efficient and convenient access to information about the environmental performance of production systems, such as agricultural systems. However, due to the mismatch between the current LCA modeling language, workflow, tool, and the systems represented, I believe that an important opportunity has been missed to capture the complexity, change, and context of agricultural systems. In this section, I describe a potential avenue through which to address these modeling difficulties.

In software engineering, the Object-Oriented paradigm came about as an attempt at capturing the essential complexity of software. Booch describes two kinds of decomposition: Algorithmic and Object-Oriented decomposition [27]. The algorithmic results in a top down structured model, declarative and directed. On the other hand, in the OO approach, one decomposes the systems using the key abstractions. Booch notes: "[In object oriented modeling,] we view the world as a set of autonomous agents that collaborate to perform some higher level behavior" [27].

Current LCA modeling utilizes a hybrid of the two, where the flow diagram is created using an OO approach, but is then quickly abandoned for a mostly algorithmic decomposition in subsequent models. Given the modeling challenges described in this chapter, I propose that a potential means to capturing the inherent complexity of agricultural systems is through a new modeling language that allows for a more object-oriented approach.

Ideally, a new modeling language would have the following capacities:

- Abstraction: A well-structured object model is used in the representation of the system.
- Composition: Objects can be grouped into components to represent subsystems.
- Modularity: Distinct interfaces between components allow for a modular system model.
- Granularity: Support for describing the system at varying levels of granularity, e.g., a high level system model, a detailed object model, etc.
- Adaptability: Support for capturing information related to how the objects and system are changed.

In addition:

- A well-defined model ontology is needed to guide the model creation process to enable reuse of domain knowledge.
- Well-designed modeling tools are needed to that support the language to enable the creation of models easily.
- Well-structured databases are needed for the sharing of models and components to enable their reuse.

A new modeling language would not be a silver bullet. It would not necessarily capture all of the complexities, changes, or context of agricultural systems, nor would it remove all accidental misrepresentation of systems. What it would hopefully do, is make the process of representing the environmental performance of such systems easier and less tedious, providing clear and distinct ways to represent and connect modular system models.

Chapter 4

Information Management in Sustainable Agriculture

Agricultural systems are composed of heterogeneous subsystems. They are prone to change over time due to rising environmental issues (such as climate change), advances in agricultural practices and technology, changing needs of an ever-growing human society, and a dynamic economic context.

Our farms are part of the highly interconnected web of industrial civilization, with dependencies on many other systems [158, 110]. Environmental impact assessments are conducted, regulations written to govern production, tools built to guide the flows of materials and products through supply chains, and food labels created to assist in consumer decision making.

At the core of these issues is a mismatch between existing environmental assessment tools and the needs of small- to medium-scale farmers (e.g., organic, urban, or otherwise environmentally conscious farmers), who do not engage in large-scale industrialized agricultural practices. In Chapter 3, I described the essential difficulties faced when modeling agricultural systems.

The goal of the work presented in this chapter, is to understand how farmers are actually structuring knowledge (i.e., creating models) related to environmental issues and resource flows on their farms and to identify what software support is wanted/needed by farmers. The primary research question of this study is:

> How do small- to medium-scale, sustainable farmers model their agricultural systems to assess environmental performance?

Specifically, how do farmers create and manage models of their farms to:

- track resource flows (e.g., water, energy, fertilizer)?
- monitor effects of the use of different cultivation methods and farming technologies?
- monitor effects of changing weather patterns?
- understand overall environmental issues on the farm?

The answer to these questions lies in the exploration of a myriad of related questions touching topics such as: farm management, regulatory challenges, economics of farming, the value of quantitative versus quantitative data, and information management. To explore these questions, I embarked on a field study, visiting 16 farms in California over two months in Spring 2016. This chapter presents the findings of this study, from the information challenges faced by farmers to restrictions encountered when modeling farms.

Chapter Overview: Section 4.1 overviews both the guiding methodology used in this chapter, the study design, and data analysis activities. Sections4.2, details the qualitative study conducted in California and presents an overview of the farmers' data collection and modeling practices. A collection of patterns and outliers found in how such farmers model the environmental performance of their agricultural systems is then presented in Section 4.3. Finally, Section 4.4 is a discussion of challenges and restrictions encountered by farmers in effectively modeling sustainable agriculture, as wells as lessons to consider in design work for sustainable agriculture.

4.1 Methodology

The Grounded Theory Method (GTM) is methodology used to develop theory about phenomena through iterative interrogation of data. GTM offers a means to explore new territory, particularly when there is a lack of dominant theory [47, 53, 151].

While the goal of this study was domain understanding, I used GTM as a means of structuring the design of this study and utilize GTM techniques for subsequent data analysis. Through use of GTM, my broader goal was to develop theories of design for sustainable agriculture.

Muller writes that one must "remain faithful to the data, and to draw conclusions that are firmly grounded in the data" [151]. I do this by iterating between recruitment, data collection, and analysis, exploring the different concepts at play, while gradually developing a theory of how to design a consistent mechanism for modeling sustainable farms and their interactions with the environment. Muller further notes,"if GTM is to serve as a way of knowing, then the knowledge that it produces should be placed in relation to other knowledge", planting the GTM-variant taken on by HCI and CSCW researchers squarely in the Straussian strain [151]. Indeed, in this study, I use the Corbin and Strauss [53] methodology that encourages searching for patterns in the data, constant comparison, and theoretical sensitivity. I also heed the practical advice Charmaz provides in "Constructing Grounded Theory" [47].

4.1.1 Study Design

In GTM, one "uses a systematic set of procedures to develop an inductively derived grounded theory about a phenomenon" [53]. The phenomenon of interest in this study in farmers' modeling of their agricultural systems when the goal is to conduct an environmental assessment. To investigate this phenomenon, three procedures were designed and conducted with each farmer-participant in person:

1. Interview: Interviews were in-depth and semi-structured, guided by a checklist, with topics ranging from farm management and record-keeping to environmental sustainability. The interviews were also guided by the needs of the participant: some interviews were split up by a lunch break, or spread over a few hours to allow for rest periods; some interviews were conducted outdoors on the farm, others at the kitchen table or while driving around the property.

2. Questionnaire: Questionnaires were designed to obtain participant demographics, as well as structured responses regarding the role and responsibilities of the participant on the farm.

3. Artifact Collection: I collected photographs, screenshots, physical copies, and sketches of: records, software, diagrams, workbooks, and other documents that came up during the interviews.

Recruitment: As the goal of this work is not to be able to make statistically significant claims about behavior, but rather to explore practices throughout the spectrum of sustainable agriculture, participants from a diverse sample of agricultural systems were required. Here, diversity refers to the type of farm, commodities produced, cultivation methods, and geographic region. As per GTM, the recruitment goal was to allow for "the representativeness of concepts in their varying forms" [53]. Therefore, in addition to inclusion criteria, a set of coverage criteria were also created to determine whether or not the pool of participants was adequately diverse.

Inclusion Criteria:

1. Sustainable Agriculture: Farmers who were already practicing, transitioning to, or interested in, sustainable agriculture were eligible to participate in the study. They had to be either currently conducting, had conducted, or intended to conduct some form of environmental assessment, formal or informal. To get a sense of the spectrum of environmental assessments possibly conducted at these farms, a set of 19 Environmental Impact Assessment (EIA) categories was created based on academic and United States Department of Agriculture (USDA) literature, as well as through consultation with University of California Cooperative Extension (UCCE) advisors [221].

2. Farm Type: While the USDA has a formal typology regarding farm size based on Gross Cash Farm Income [235], we were advised by UCCE advisors to allow farmers to self-identify, as this typology is still evolving. Therefore, farmers who self-identified as small- to medium-scale family farmers were eligible to participate in the study.

3. Sales: The farmers had to be producing food for sale to the public, for example, through direct sales, community supported agriculture (CSA) sales, on-farm markets, farmer's markets, and/or wholesalers. This simply excluded purely hobby and/or subsistence farmers.

Coverage Criteria:

1. Commodity Types: At least one farm covering each of the following categories was included in the study: field crops (e.g., rice, corn), tree crops (e.g., oranges, almonds),

vine crops (e.g., grapes), vegetable crops (e.g., spinach, squash), and livestock (e.g., poultry, meat). These categories were created in consultation with a UCCE advisor.

2. California Farming Regions: At least one farm from the three agricultural regions of California [219]: the North Coast and Mountain region, the Central Valley, and the Central Coast and Southern region, was included in the study.

Participants were primarily recruited via phone calls. Farms that fit both inclusion and coverage criteria were selected from the following public directories: USDA National Farmers Markets [229], USDA On-Farm Markets [230], Local Harvest [134], Certified Naturally Grown [45], Demeter Biodynamic Certified [58], and the Organic Integrity Database [232]. Participants were also recruited via handouts at farmers' markets, social media, recommendations from UCCE advisors, and through snowball sampling. In all cases, a recruitment follow-up call was placed to confirm participant eligibility as per the inclusion and coverage criteria.

4.1.2 Analysis Techniques

Three analysis techniques were used in this study. The results of these activities culminated in the formation of a grounded theory [53] that informs the design activities presented in Chapter 5. Prior to analysis, interviews were literally transcribed, and the non-digital artifacts were digitized.

Coding Interviews: First, each of the interviews were coded using three rounds. While these were conducted linearly the first time through, I jumped between these processes in subsequent iterations depending on which data required deeper analysis or a step back. Each of these rounds resulted in increasingly abstracted concepts.

1. Round One, Low-level Concepts: Interviews were annotated using the “incident-by-incident open coding” [47] technique. Actions and processes were analyzed to identify key concepts.

2. Round Two, Categories: Interviews were revisited, this time, related concepts were tagged with categories. Figure 4.2 shows a round two coding sample.

3. Round three, Core Categories: By this point in the coding process, all three types of analysis (coding interviews, coding artifacts, and artifact trails) were being conducted concurrently. As themes emerged in the data, core categories were created to allow for reflection on the information management practices of the interviewed farmers. These resulting categories are described in Section 4.3 of this chapter.

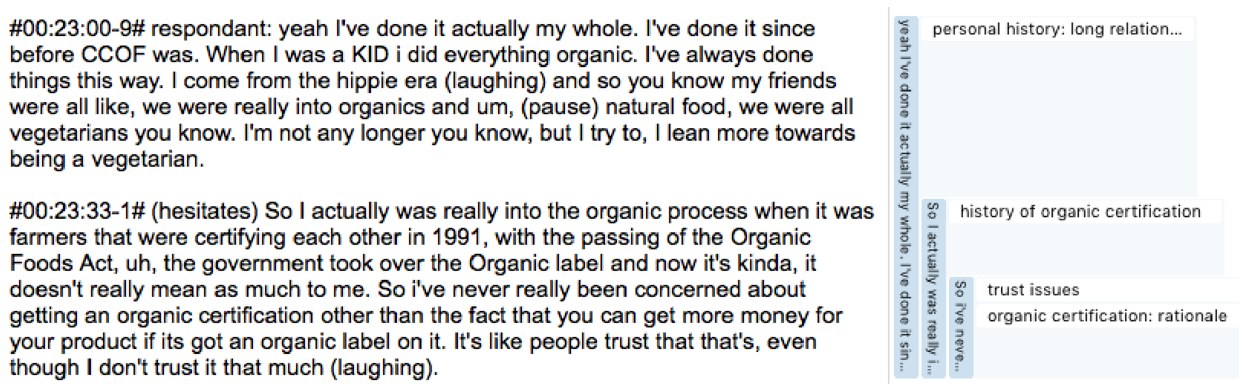


Figure 4.1: Sample interview coding: Round two.

Coding Artifacts: Next, each of the artifacts — photographs, drawings, screenshots, worksheets — were coded individually. Each artifact was initially treated in the same manner as the interview data. Then, in round two, artifacts and interviews were connect, with all data finally coming together in the artifact trail creation activity described later in this section.

It is important to note that not all farms had artifacts. Further, the level of detail in artifacts, the number of artifacts, and the coverage of farm structure and activities, all varied between each set of artifacts. However, if during an interview, a farmer described an artifact with sufficient detail, the description snippet was used as an artifact stand-in.

1. Round One, Low-level Concepts: Each artifact was coded in a similar manner to the round one coding of the interviews. Here, the concepts that were annotated described what the artifact contained.

2. Round Two, Connecting Artifacts to Interviews: All artifacts were collected over the course of the interviews. Whether it was a photograph of a map on a wall, or a screenshot that the farmer emailed me after our conversation, each of these artifacts have a point of origin in the interviews. In this round, I reconnected each artifact to the original interview, seeking context for artifact collection, farmer descriptions or rationale for what is contained, as well as any supplementary information about the artifact, e.g., use or non-use, or where it was collected.

3. Round Three, Core Categories: Core categories were then created across the collection of artifacts. A sample annotation is shown in Figure 4.2. This is the same activity as previously described for round three of the Coding Interviews activity.

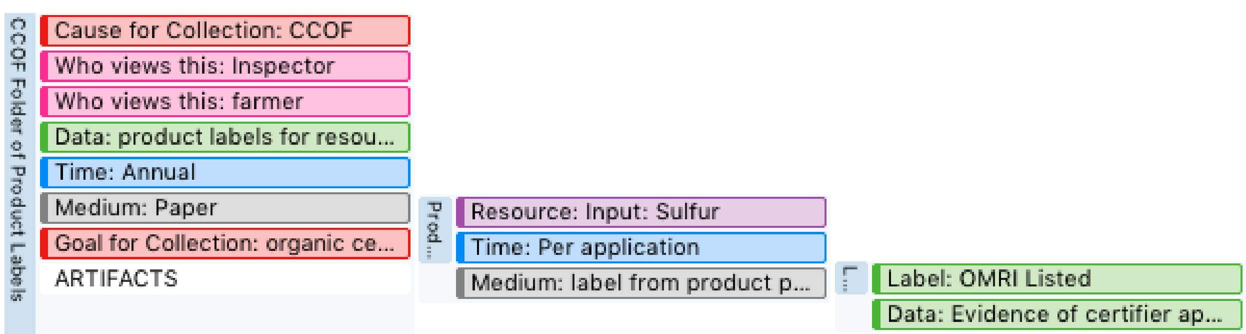


Figure 4.2: Sample artifact coding: Round three. The original artifact (not pictured) is an image of folder containing product labels for all farm inputs that season, intended for submission to the farm's Organic Certifier.

Artifact Trails: During the process of connecting artifacts to interviews, it became apparent that there were specific forms of transformation that the data underwent as it was collected, used, and manipulated in different ways at each farm. To get a better sense of the life cycles of information and the role of these artifacts, I created *artifact trails*. Each of these trails track a specific attribute of the artifact. The three most useful artifact trails were those which:

1. Tracked flow of information: Artifacts were connected in a directed graph from the point at which data was collected, through each transformation, to the point at which it was presented outside the farm system.
2. Tracked changes in medium of technology: The previous artifact trail was further annotated with the medium of technology (e.g., paper, email, spreadsheet) that was used to collect, structure, transmit, or manipulate the data contained.
3. Identified concept clusters: Artifacts were connected to each other based on common data structures to identify the foci of representation.

A sample artifact trail is shown in Figure 4.3 below.

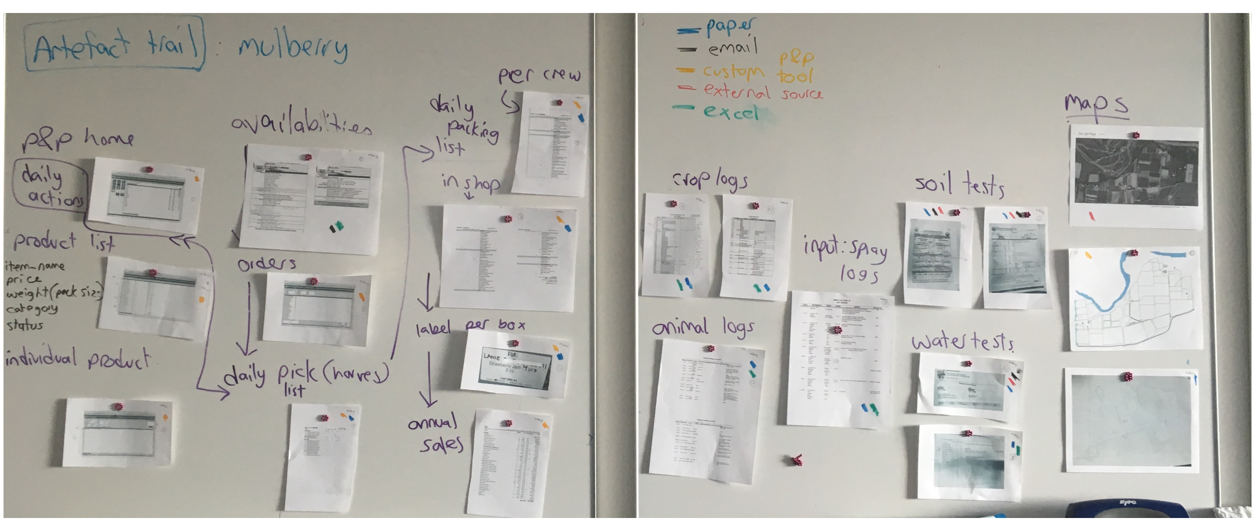


Figure 4.3: Sample artifact trail, tracking the flow of information through a farm.

4.2 Sustainable Agriculture in California

4.2.1 Farms and Participants

In total, there were 16 participating farms (A to P), with 19 participants. An overview of each of the participating farms is avaialble in Table 4.1.

At three farms, two people were interviewed. Both participants and farms are referred to by pseudonyms, to assist in tracking participant-farm relationships, the first letters of the farm and participant pseudonyms are the same: e.g., Carol and Charles, Campbell Farms. Artifacts have been scrubbed of identifying information to protect privacy, ensure anonymity, and reduce bias.

Each of the three farming regions, — the North Coast and Mountain region, the Central Valley, and the Central Coast and Southern region — encompass diverse climates, geographies, cultures, products, and agricultural systems. Coverage of all regions would not have necessarily resulted in coverage of the full diversity of farm types, as farms vary widely within regions, resulting in many further subdivisions. Therefore, while we did not manage to recruit any farms from the North Coast and Mountain region, the farms that did participate still represent a broad range of agriculture in California. The participating farms were from 10 California counties, as far north as Butte County and as far south as San Diego County, and farming landscapes ranged from coastal farms in Ventura and San Diego Counties, to hilltop farms in San Luis Obispo and Yolo Counties.

Of our participating farmers, 6 were first generation farmers and the other 13 came from families that had been involved in farming for at least two generations. Participant ages ranged from 30 to over 75. The ownership structure of the farms was mostly either family-owned or a sole proprietorship.

Not all people interviewed at the farms were farmers per se: for example, at Marsden Organic Farms, Marla, the daughter of the farm owner-operator, is primarily involved in outreach, education, sales, and marketing on the farm. At the Davies Aquafarm, Daria, the hatchery manager was interviewed. In all cases, the participant had significant or final decision making authority or influence (as reported in their questionnaire).

Codename	**Commodity**	**Primary Products**	**Region**	**Years Active**	**Self-Categorization**	**Certi-fications**	**Environmental Concerns**
Atwood Organic Vineyards	Tree & Vine crops	Grapes	✚	~30	Organic	Organic	Wildlife habitats
Brooks Organic Farm	Tree & Vine crops; Vegetable crops	Fruit & vegetables	✚	>25	Organic	Organic	Pollinators & habitats
Campbell Farms	Field crops; Tree & Vine crops; Vegetable crops	Fruit & vegetables	✚	>25	Sustainable	None	Pollinators & habitats
Davies Aquafarm	Livestock	Shellfish	✚	~30	Sustainable	None	Water, climate
Eco Ranch	Livestock	Meat & animal products	✚	13	Sustainable	None	Animal welfare, recycling
Frost Farms	Field crops; Tree & Vine crops; Vegetable crops	Fruit & vegetables	✚	20	Sustainable	None	Land use
Glass Organic Orchard	Tree & Vine crops	Tree fruit, grapes	O	~50	Organic	Organic	Resilience, Soil health
Huang Integrated Aquafarm	Tree & Vine crops; Nut crops; Livestock	Fish & water plants, grapes, nuts	O	~50	Integrated, Conventional	None	Wildlife habitats, water, recycling
Iyer Orchards	Nut crops	Almonds	O	12	Conventional	None	Soil health
Jordan Hives	Livestock	Honey	O	>25	All natural	None	Pollinators & habitats
Kent Organic Orchard	Nut crops	Walnuts	O	>25	Organic	Organic	Soil health
Lowry Fields	Field crops; Livestock	Rice, beef	O	55	Conventional	None	Water, land use
Marsden Organic Farm	Field crops; Tree & Vine crops; Nut crops; Vegetable crops; Livestock	Fruit, nuts, & vegetables, meat & animal products	O	~32	Sustainable	Organic	Pollinators & habitats, water
Newton Ranch	Livestock	Meat & animal products	O	~4	Sustainable	None	Animal welfare, land stewardship
Orwell Organic Greenhouses	Vegetable crops	Micro-greens	O	~30	Organic	Organic	Composting
Pullman Biodynamic Vineyard	Tree & Vine crops	Grapes, olives	✚	~15	Biodynamic	Biodynamic	Water, land stewardship

Field crops
Tree & Vine crops
Nut crops
Vegetable crops
Livestock

◆ North Coast & Mountain
O Central Valley
✚ Central Coast & Southern

Table 4.1: Summary of participating farms.

4.2.2 The Spectrum of Sustainability

Stewardship of land and water and the relationship of the farm with local wildlife was a prominent theme that came up during the interviews. Farmers described the interplay between their farms and the environment, taking delight in their relationship with nature. This delight is certainly not something quantifiable, or adequately expressible through environmental certifications and analysis tools alone.

Farmer Carol, of Campbell Farms, said: *"We're stewards of the land. I love the wildlife; I would never want to harm it with the way I'm farming. [...] A year ago, there were this little birds called killdeer, they nest on the ground. One of them had a nest, so we went around it. And we let her have her babies you know? [...] We're trying to preserve and promote the wildlife in our farm and a lot of times the animals are attracted to the farm because it's a safe haven. There's water and there's food."*

In the 2010 report, "Toward Sustainable Agricultural Systems in the 21st Century", the National Research Council (NRC) defines four goals that a sustainable agricultural system should meet: the ability to satisfy human food needs; sustained economic viability; enhanced quality of life for farmers, workers, and society; and enhanced environmental quality [158]. However, this report also concludes that "no simple typology or set of categories can capture the complexity of the farming practices and systems used on diverse U.S. farm systems" [158], and that the lack of such a typology complicates our understanding of what it means for a farm to be sustainable.

Indeed, agricultural systems are not binary: it's not that they're either conventional or sustainable, but there exists a "farming systems continuum" [158]. Based on our findings, we posit that a typology of farms is not necessary, and that instead, the ability to express the spectrum of sustainability may suffice.

Each farm subscribes to a set of core values. These are not always reflected by their certifications or through any official designation. We often found a discrepancy between each farm's self-categorization and environmental values versus certifications.

As Farmer Carol pointed out: *"We might not be certified organic farm, but do you think all this wildlife is gonna be here if there were all these chemicals?"*

In fact, we found that sometimes farmers would actively not pursue certifications because of the mismatch between certification requirements and their own values.

Farmer Earl cautiously described the implied tradeoffs: *"We don't use herbicides or pesticides, although we want to reserve the right to use an antibiotic on an animal if it won't heal naturally. It's inhumane to let an animal suffer if it can't be healed naturally. What would you do? We use penicillin. It's an antibiotic. You can't do that if you're certified organic, you have to let it suffer."*

However, farmers do appreciate the value of certifications, particularly as they as lower the barrier to practicing and being acknowledged for practicing more sustainable agriculture.

Farmer Kyle notes: *"Ultimately you gotta pick a spot and draw that line. So if somebody is walking the right along the edge of the line, are they doing the spirit of organic? Better than the guy who doesn't care and isn't trying."*

The current landscape of environmental certifications and labels, from Organic [231] to Biodynamic [58] all require a farm to either self-categorize as such, or not — for instance, a farm is either organic, or not. Any deviation from the checklist results in non-compliance. There is also no room for expressing that the farm is going above and beyond what is required by a certification.

These values are not always quantifiable and have resulted in the "know your farmer" movement [234]. But given the fact that farmers do have farm data, both qualitative and quantitative, means that there are opportunities to know the farmer through their data. Many farms already use a variety of means of communication: talking to folks at farmers' markets and on-farm market stands; pamphlets, books, and interaction with traditional media; and through websites and social media.

Farmer Charles describes different channels of communication utilized at Campbell Farms: *"[We maintain a] website and keep it current daily with what we have fresh in the stands now. [... L]etting people know what's in season, providing pictures and videos of what's going on at the farm and news interviews that we've been in. Then we also do social media because that way people can see what we're growing and what it looks like, and know what's in season and what's in the stand this week. Oh look at that, they got strawberries you know. So Facebook, Twitter and Instagram. And then email also. All this is a constant part of weekly updates."*

Farmers collect environmental data to enable the pursuit specific environmental certifications, to meet environmental regulations, and to participate in incentive programs. Farmers also collect environmental data to be able to reflect on the environmental performance of their farms and to provide evidence of how they meet their chosen instantiation of sustainable agriculture. Given the spectrum of sustainable agriculture, how can we more effectively design for value complexity?

4.3 Findings: Farm Data

Farmers collect a great deal of heterogenous data, both qualitative and quantitative. They subsequently create many models, both explicitly and implicitly. Both data and models are subject to many restrictions, both social and technological, and these restrictions vitiate the true value of the data.

Some data collection is driven through regulatory requirements or through seeking specific farm-level certifications (e.g., USDA organic). Other data are collected for a farmer's internal economic (e.g., labor and sales data) and environmental performance (e.g., water quality and soil health).

Please note, all images of farm models shown in this chapter were artifacts collected during the on-farm interviews: these artifacts were introduced in Section 4.1. These models were already created by the farmers, some of whom sought assistance from friends, UCCE advisors, professional software developers. Some models were regularly used in farm activities, some models were simply part of a farm record, and others were created but unused or repurposed.

4.3.1 How do farmers collect data?

There are three methods farmers use to collect farm data: through observation, collecting and testing samples, and the use of instruments such as sensors.

4.3.1.1 Observing the farm

Farmers collect a nontrivial amount of semi-structured data through direct and continuous observations. These data are often split across paper journals, post-it notes, and emails, among other media. This data is often qualitative, descriptive, and often involves *"walking the fields"* on a regular basis. Careful observation is one of the most crucial data collection methods for sustainable farmers.

Farmer Gina described this further: *"We work with a lot of data, but data comes in different forms. So lots of being in and walking the fields. lots of, lots of tracking weather. And looking at the moisture content of the soil, sort of like, my dad has a better sense of- it's still a little mystical to me when we have to water! [...] [A] lot of what we do is very old fashioned in* *term of: we just spend a lot of time in the fields. Walking, driving, we're just, by virtue of living here, we do a lot of visual observation of what's happening."*

4.3.1.2 Sampling the farm

Farmers engage in a range of sampling activities. Most often, soil and water samples are collected and sent to labs to test for microbial content, contaminants, and other properties. Farmers also sample crops and animals to obtain, for example, how productive a tree is or how healthy a herd of sheep is. The frequency, formality, and types of sampling farmers conduct depend on what their certifications, if any, require, and if they need lab tests to complement their knowledge of what is happening around the farm.

For example, Farmer Marla reported that at Marsden Organic Farms, they conduct annual water tests for both food safety reporting and to keep tabs on their boron levels. However, Farmer Hari, at the Huang Integrated Aquafarm only conducts water tests if an unexpected issue arises, as he consistently checks water alkalinity through observations and at-home pH testing kits.

4.3.1.3 Instrumenting the farm

While there is interest in using sensing technology, none of the participating farmers relied on sensor data on a regular basis. However, there is an interest in instrumenting the farm to obtain more granular and continuous data about various subsystems on the farm.

Farmer Irfan, from Iyer Orchards, described a set of *"depth sensors for the water"*, that his previous co-farmer installed throughout the almond orchard to get a sense for how water permeates through the soil during irrigation. Farmer Hari had similar sensors in his orchards, but both farmers stated that these sensors were no longer in use as they did not know what to do with the data.

4.3.2 What data do farmers collect?

The following categories of farm data are collected: environmental data, resource data, and operational data.

4.3.2.1 Environmental Data (regarding farm context)

Much of the environmental data collected by farmers is collected is observation or external consultation, recorded in unstructured formats, used for informal assessments of environmental performance, and often reported anecdotally.

Weather: Many farmers check the weather forecast via online websites like AccuWeather [1] or consult the National Weather Service [156]. This data is consulted and compared to personal weather records to plan hourly, daily, and sometimes weekly activities.

Farmer Paul, of the Pullman Biodynamic Vineyard, described his process: *"I get information everyday from our local weather, vineyard weather people. And they tell you all sorts of things: growing days, sunlight hours, [and] powdery mildew. [...] Very good, very detailed. So, you know, I look at those growing days in comparison to other years; think about our actual weather... have we been having a lot of wind? And I might go back and look at my notes of course, everybody does that!"*

Land: Farmer Kyle, from Kent Organic Orchards, described how over the years, as they have learned more and more about the soil composition of their land, they have adapted their farming techniques and even crops grown. He described the soil data they have accumulated: *"We've taken soil samples, but we deliberately take soil samples from those different regions because we know they're different. We have done a survey where the fertilizer company [...] mapped the soil of the entire property and we got a cool map that shows the different kinds of soil on the surface."*

Weeds and pests: *"No weed is bad,"* said Farmer Alex of Atwood Organic Vineyards, *"Actually the word weed, just means a plant that's in the wrong place."*

Many of the farmers we spoke with described how weeds and pests indicate and affect land and crop health. They monitor occurrences of different types weeds and pests and any interventions they implement, to be able to assess the efficacy of the interventions (such as use of cover crops or biological controls), as well as the effects of the weed or pest's presence.

4.3.2.2 Resource data (regarding farming inputs)

The range of farming inputs, frequency of data collection, and complexity of data formats depending greatly on the type of commodities grown and the complexity of the farm.

Water: Most farms track water quality, consumption, and runoff. The granularity of these data as well as reasons for data collection varies widely depending on commodities, county, and interest. The three primary causes of water data collection are for various water and environmental management regulations, food safety regulations, and for internal assessment and decision-making.

One of the annual water quality tests from Marsden Organic Farms indicates the Most Probable Number of the analyte per 100ml of water (MPN/100ml) [227] of E. coli were found in a sample collected at a particular water pump. Other water sampling points include:

wellheads and other water sources like creeks or ditches, areas of the farm where crucial activities are occurring such as washing or packaging of greens, or at various points in an irrigation line. For the most part, water quality tests are conducted by sending samples to a third-party lab for testing, with results coming in via post and email. After review, these are simply filed away for future reference and reporting.

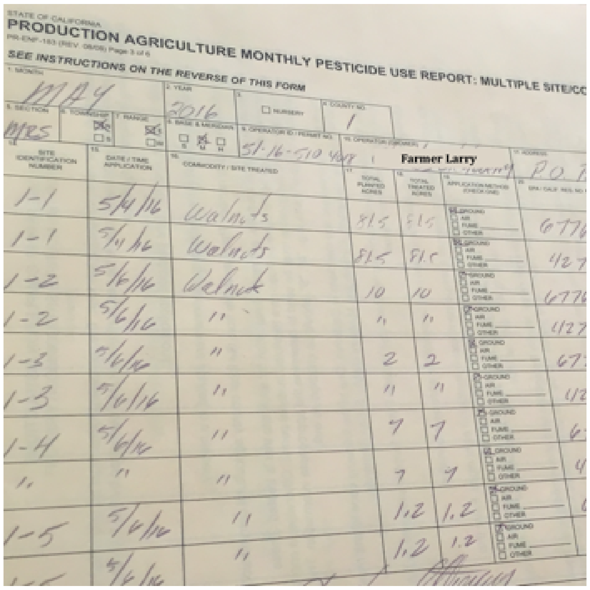
Monitoring water consumption at Frost Farms involves checking each water meter and recording how many gallons of water were applied to each crop in each field. This is primarily done to meet regulatory requirements regarding groundwater management.

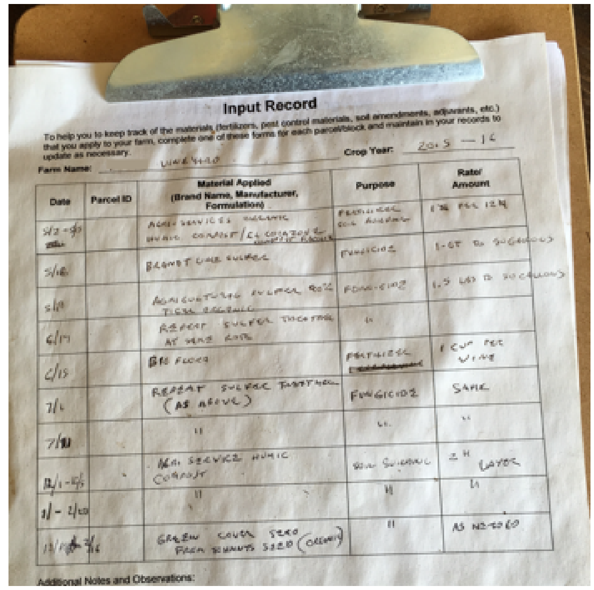
Farmers also track water runoff and discharges (including sediment) to the land and local water bodies, e.g., tracking water quality at drains or other places where resources exit the agricultural system. Glass Organic Orchards is part of local coalition that represents almost all farmers within their watershed, thereby pushing the responsibility of water testing, data collection, and aggregation for this purpose to the watershed level.

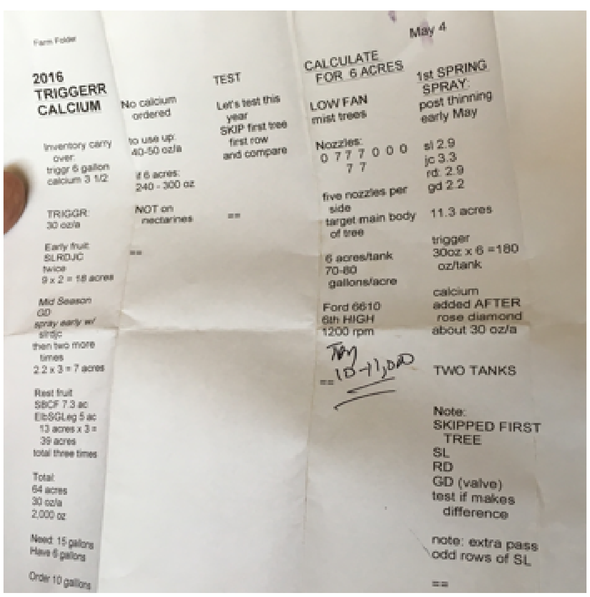
Soil amendments, pesticides, and other material inputs: Previously described agricultural regulations require farmers, conventional or sustainable, to keep track of pesticides, fungicides, herbicides, and other chemical inputs to the land. Certain conditions (county, farm type) may also require farmers to keep track of fertilizers or other soil amendments. Various sustainability-oriented certifications, such as those available through the U.S. National Organic Program, also require tracking of organic inputs [231].

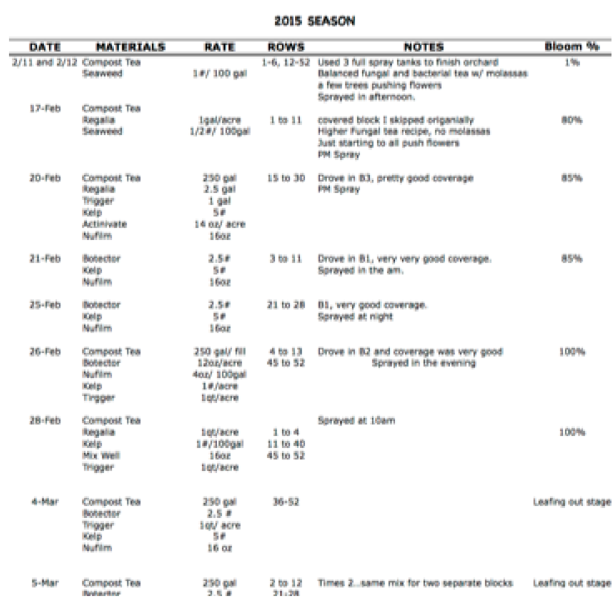
Such input data are typically logged per application per unit space. Log format and medium depends on the commodity type, regulations, and farmer preferences.

For example, Farmer Larry, who grows rice and walnuts conventionally at Littlewood Fields, has to submit a monthly pesticide use report (Figure 4.4, top left (page 102)). Each time a product is applied to a particular field, he notes which product was applied, what is grown there, rate of application per acre, dilution of product in medium (e.g., water) and other pertinent details. Each month, he fills out the relevant California state forms and submits them his county office.









2015 SEASON

DATE	MATERIALS	RATE	ROWS	NOTES	Bloom %
2/11 and 2/12	Compost Tea Seaweed	 1#/ 100 gal	1-6, 12-52	Used 3 full spray tanks to finish orchard Balanced fungal and bacterial tea w/ molassas a few trees pushing flowers Sprayed in afternoon.	1%
17-Feb	Compost Tea Regalia Seaweed	 1gal/acre 1/2#/ 100gal	 1 to 11	 covered block I skipped origanially Higher Fungal tea recipe, no molassas Just starting to all push flowers PM Spray	 80%
20-Feb	Compost Tea Regalia Trigger Kelp Actinivate Nufilm	250 gal 2.5 gal 1 gal 5# 14 oz/ acre 16oz	15 to 30	Drove in B3, pretty good coverage PM Spray	85%
21-Feb	Botector Kelp Nufilm	2.5# 5# 16oz	3 to 11	Drove in B1, very very good coverage. Sprayed in the am.	85%
25-Feb	Botector Kelp Nufilm	2.5# 5# 16oz	21 to 28	B1, very good coverage. Sprayed at night	
26-Feb	Compost Tea Botector Nufilm Kelp Tirgger	250 gal/ fill 12oz/acre 4oz/ 100gal 1#/acre 1qt/acre	4 to 13 45 to 52	Drove in B2 and coverage was very good Sprayed in the evening	100%
28-Feb	Compost Tea Regalia Kelp Mix Well Trigger	 1qt/acre 1#/100gal 16oz 1qt/acre	 1 to 4 11 to 40 45 to 52	Sprayed at 10am	 100%
4-Mar	Compost Tea Botector Trigger Kelp Nufilm	250 gal 2.5 # 1qt/ acre 5# 16 oz	36-52		Leafing out stage
5-Mar	Compost Tea Botector	250 gal 2.5 #	2 to 12 21:28	Times 2...same mix for two separate blocks	Leafing out stage

Figure 4.4: Resource tracking in sustainable agriculture. *Clockwise from top left:*
(1) Littlewood Fields: CA pesticide use report,
(2) Atwood Organic Vineyard: CCOF input record,
(3) Marsden Organic Farms: Internal spray log per field,
(4) Glass Organic Orchard: Internal calcium spray log.

Similarly, Farmer Alex uses the California Certified Organic Farmers (CCOF) [32] Input Record form to track all organic inputs (Figure 4.4, top right (page 102)). This specific record is a little less detailed, but when taken in consideration with all the other records CCOF requires, the data contained are essentially the same: at each product application, he notes which product was applied, the parcel it was applied to, the purpose of application, and the rate or amount. Alex is also the sole farm manager and has no need to share what he tracks on his clipboard with anybody other than the CCOF inspector once a year.

At Marsden Organic Farms, on the other hand, there are anywhere between four to eight farmers working together to produce several different kinds of food. They also make heavy use of their own record keeping techniques (Figure 4.4, bottom right (page 102)). As a larger farm with a bigger workforce, a major area of focus for them is to enable collaboration among the farmers. They have a series of Excel spreadsheets and other records for different farm activities and a central office with dedicated managers who assist in farm coordination.

Finally, Farmers Gina and Gary, of Glass Organic Orchard, use a variety of homegrown formats and tracking methods to engage in analyses of the efficacy and environmental performance of various inputs (Figure 4.4, bottom left (page 102)). These formats contain fine-grained data, blending qualitative notes with quantitative samples, and still have at minimum, the data required for their organic certification.

4.3.2.3 Operational data (regarding farm management)

Much data collected by farmers revolves around farm operations. Farmers track process, people, and money. Common categories of operational data were for planning and management; field productivity; sales and finances; labor; and machinery and equipment. These data are core to the business of farming. As such, most farmers did not allow for artifacts relating to operational data to be collected, though they were discussed during the interviews. The rest of this chapter therefore focusses on data related to inputs, the environment, and field operations.

At each of farms with livestock a whole range of records is also kept to track animals including breeding, vaccination, and medical records. Due to the sensitive nature of such data, most farmers did not share these data either during the interviews. Therefore, most of the data discussed in this chapter is regarding the plant-based subsystems at these farms.

4.3.3 Who are the stakeholders of farm data?

The set of stakeholders of farm data includes, at minimum: the farmers and farm workers; consumers; retailers and brokers; inspectors and regulators; and external advisors and analysts. Each of these groups uses farm data, either directly or indirectly, for daily decision-making and problem solving.

Each of these stakeholder groups use farm data for the following types of activities:

- *Analysis:* Activities range from economic analyses and environmental assessments, to internal reflection on farm performance with respect to the farmer's priorities.
- *Coordination:* Activities range from coordinating farm activities with workers to coordinating sales with brokers.
- *Communication:* Activities range from regulatory and certification purposes to consumer awareness and education.

4.3.4 How do farmers model farm data?

Farm models tend to either focus on a particular commodity or a process. In the same vein, they would represent either the spatial or temporal dimension of the farm. In this section, I describe how each of the farms, Atwood (A) through Pullman (P), capture and track, space and time.

4.3.4.1 Representing Space

The farms occupied a range of physical distributions and layouts. These physical structure of the farm depends on the type of crop(s) grown, presence of livestock, environmental goals, farming practices, and other characteristics of the farming operation. In turn, these determine the what kinds of spatial representations of the farm are created and used.

First, consider the spatial distribution of each of the farms shown in Figure 4.5:

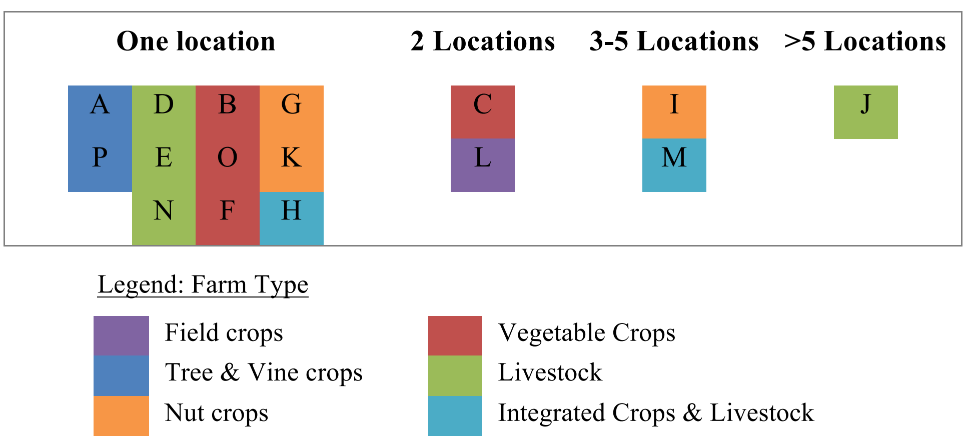


Figure 4.5: Spatial distribution of each of the farms, Atwood (A) through Pullman (P).

Majority of the farms were located at a single site. Both Cambell Farms and Lowry Fields consisted of two sites. Different products were grown across each of the sites, where the day-to-day operations of each site were managed relatively independently, with the main farmer splitting time and coordinating between sites. At Iyer Organic Orchards, the same orchard style was simply replicated at each site.

Marsden Organic Farms, while spread across several sites, integrated certain aspects of farm management across the sites, but subdivided field-level operations within sites. While the farm was distributed across space, the farmers and collaboratively farmed the land across all farm sites, in effect treating it as they would have a single site.

The outlier on this distribution is Jordan Hives. This beekeeping operation is distributed over the greatest number of locations as the beekeeper, Jack, places groups of hives on other farmers' properties to pollinate their orchards and fields. The primary location, Jack's home, contains a honey processing facility, a queen breeding and hive splitting operation (to produce new hives), and a small pollinator-friendly garden. Given this dynamic spatial distribution of the hives, Jack uses a mobile application specifically designed for tracking hives and other beekeeping activities. Data contained includes: location, hive numbers, and the date the hives were moved to location. This allows Jack to keep track of his spatially distributed agricultural system.

Figure 4.6 (page 107) shows four spatial representations used in different types of agricultural systems. The hand-drawn Pullman Biodynamic Vineyard map (Figure 4.6, top left (page 107)) was originally intended to communicate to visitors to the on-site winery what varieties of grape are grown, and which different systems exist to support the environmental sustainability of the property (e.g., beehives for local pollination, compost yard to deal with organic waste). As location of the vines doesn't change frequently, such a model would not need to be updated on a regular basis. However, the farmers reported that this map had been opportunistically used to coordinate activities, such as pruning and harvesting, among the four family members who work on the farm.

In contrast, Marsden Organic Farms have detailed field layout diagrams (Figure 4.6, top right) for each property based on satellite images that are available through a customized FileMaker [72] database application. While the rest of the application is heavily used to coordinate sales, customer orders, and harvest-related activities, these maps are entirely unused as the turnover of crop in each field is high.

Figure 4.6: Farm layout diagrams. *Clockwise from top left:*
(1) Pullman Biodynamic Vineyard,
(2) Marsden Organic Farms,
(3) Glass Organic Orchards,
(4) Osborne Organic Greenhouses.

Glass Organic Orchards and Osborne Organic Greenhouses seem to have found a middle ground in representing useful information through spatial representations. Glass Organic Orchards (Figure 4.6, bottom left (page 107)) use a box and text layout diagram of the L shaped property to demarcate irrigation lines, power lines and tree varieties. At Osborne Organic Greenhouses, they use a similar box and text layout diagram to mark where pest-related interventions, such as mousetraps, have been placed (Figure 4.6, bottom right (page 107)). A duplicate of this map exists for indicating flytraps. These maps are used both for communication among farm workers, as well as for CCOF reporting. As the crops themselves are on a two-week harvest cycle they do not use this map for crop locations.

Structurally static farms do not typically use spatial representations in daily farm activities. For example, Iyer Orchards was comprised of four noncontiguous 40-acre fields within an approximately 4-mile radius and with almost identical layouts at each site. Each was planted a few years after the next as Irfan made staggered land purchases. While his orchards are geographically dispersed, they are each treated as independent systems, with little interaction between the fields across space. Both the farming and modeling practices are simply replicated at each location with minimal customization as each of the fields are very similar in geography and environmental context.

Littlewood Fields is arguably similar in spatial complexity. The primary location consists of several rice fields, each approximately 40 acres and tens of acres of pasture. The second location serves only as a winter pasture for Larry's cows. Here too, no spatial representations are used on daily basis with Larry relying on a visual survey of his fields to determine field status and plan the next set of activities.

Both Iyer Orchards and Littlewood Fields were also closer to the conventional side of the farming spectrum. At each farm, approximately the same inputs were applied to the fields each season, and the farm layouts were designed to optimize yield. This uniformity diminished the need for much spatial representation, with most of their records revolving around input tracking for internal assessments and regulatory reporting.

4.3.4.2 Representing Time

Farms are dynamic and cyclical in nature; however the level of dynamism and length of cycles depends on the commodities grown on the farm. Major activities and thus the pace of the farm are dictated by the speed of plant growth or the more urgent needs of the animals. Variability in farm activity frequency is also closely tied to seasons and overall life cycles.

Consider the temporal distribution of activities at each of the farms shown in Figure 4.7:

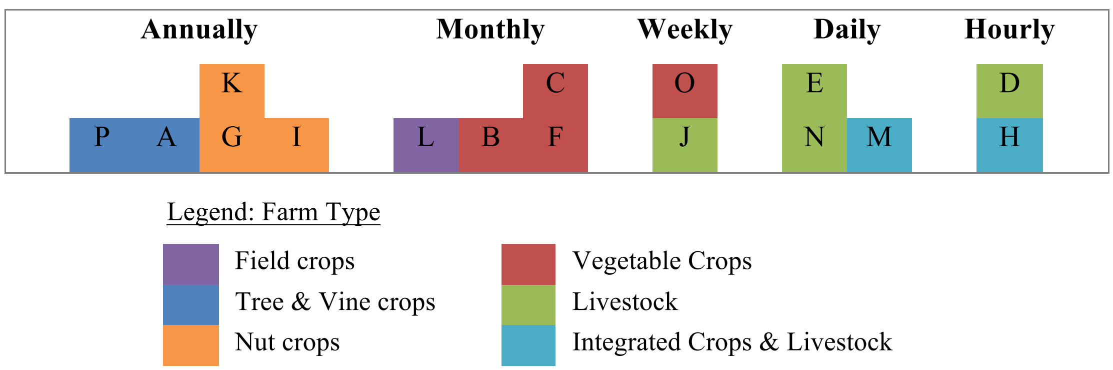


Figure 4.7: Temporal distribution of each of the farms, Atwood (A) through Pullman (P), based on frequency of major activities.

At Jordan Hives, bees are monitored approximately weekly, and mostly moved during pollination seasons. Over the winter, the bees are mostly dormant. However, farms with any form of livestock have at least daily activities, regardless of season, as the animals need to be fed and cared for. Farm with fish and shellfish require close monitoring of water quality and temperatures, and therefore tend to have near-hourly monitoring. True hourly monitoring tends to occur on farms with hatcheries or animal breeding programs.

In crop agriculture, micro- and baby-greens have the shortest cycles. For example, the micro-greens grown at the Osborne Organic Greenhouses are on a two-week cycle, as that is how long it takes from seed to harvest. The farm with the longest activity cycles and slowest rate of change was Pullman Biodynamic Vineyard, as one of their core values involves minimal interference with the vines and the practice of dry farming. Nevertheless, orchards and vineyards tend to operate on annual cycles. Field and row crops are on monthly cycles, with organic crops growing at a slightly slower pace than conventional crops.

Kyle explains: *"Organic inputs are more expensive than conventional inputs [...] because [...] they don't have that 30 day or 60 day or 90 day cycle of breakdown and release that's much faster. [...] With [the] organic products that we're adding for soil, it is a 6 months to a year breakdown time. And for certain soil amendments, the minerals, trace elements, and other things that we add, it's a multiyear process. [...] You have to look further ahead and kind of project what your input needs are going to be to be able to balance them over time, because you don't have that quick response time that you have on the conventional side."*

All farms use a calendar to represent time. What varies is the granularity at which farmers track farm activities and the structure of the representations used. These often take the form of a linear calendar, similar to the calendar Gina uses to schedule farm activities at Glass Organic Orchards (Figure 4.8, page 111).

At the Glass Organic Orchard, Gina has been experimenting with modeling structures with respect to representing time and activities on the farm. For example, she created several wheel-based calendars to track time, activity, anomalies, and change over a year of tending to an orchard (Figure 4.9, page 111). She also has activity-specific records and data structures: e.g., to track resource use and labor during the pruning season, she first uses paper-based index cards, and subsequently enters this into another spreadsheet.

	Field Work or Management work	Hired Labor	Admin Jobs	Research / Intellectual
After Harvest	Shaping			
October	Chainsaw			
	Blow off leaves to start dormancy early?? (especially elberta/legrand?)			
November	Chainsaw & stacking & Bucking		Order replants?? (or earlier?)	track chill hours
	(every other year burn permit / burn wood?)			
December	Prep Pruning Plan			
		Tree Pruning	Taxes	
	Shred trees (ready for dormant sprays and roping)		(order dormant spray / phermones?)	
	Tag Vine Runners			
	Plant vine Runners ahead of pruning/tying			
January	(dormant sprays)		(county pesticide application forms - monthly)	
	Disk trees (cross first, then length, so sprayer is less bumpy)	Vine pruning		
	Plant re-plant trees	Tree Roping		
	Shredding vines			
	Plant Runners			

Figure 4.8: Representing time at Glass Organic Orchard: Gina's traditional calendar.

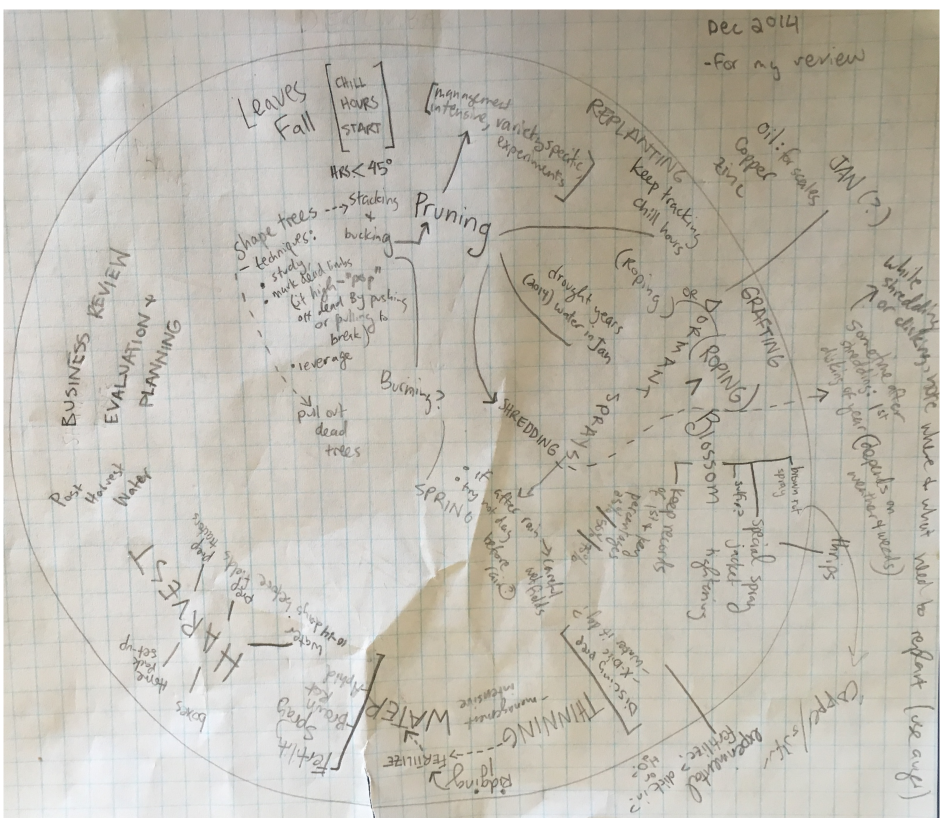


Figure 4.9: Representing time at Glass Organic Orchard: Gina's wheel-based calendar.

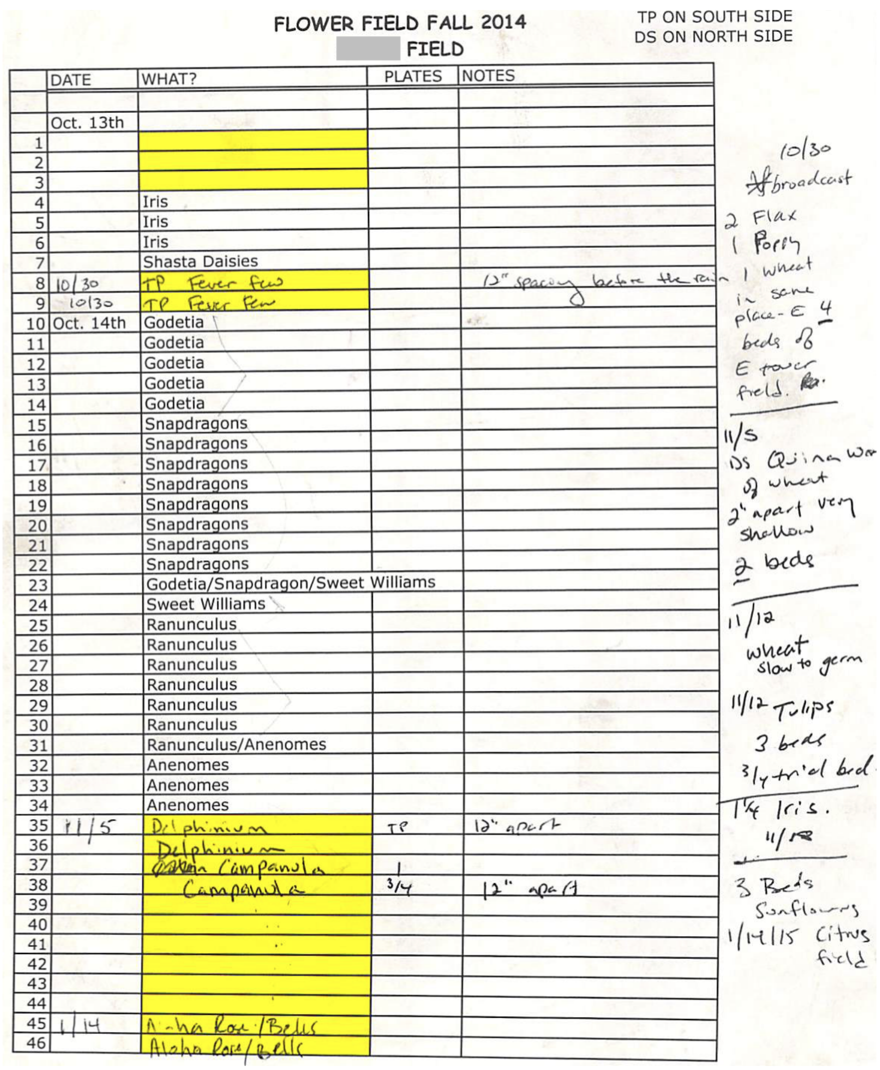
4.3.4.3 Combined Representations of Space and Time

Many models are used to track specific commodities across both space and time.

For example, crop rotation at Brooks Organic Farms occurs every few months, demanding representation of crop locations as they change over time. Prior to each new planting, the farm manager traces an outline of the farm layout onto a new sheet of paper as shown in Figure 4.10. He marks the date, and labels each field with what crops are currently there, signing off the field as it is harvested. They have a binder containing farm layouts dating back several years so that they may track what has been grown, and where. This allows them to plan out relevant soil building activities (e.g., planting nitrogen-fixing crops), report data required for regulatory and certification-related purposes, and engage in daily farm management.

Figure 4.10: Representing space and time: Brooks Organic Farms, farm layout 11 February 2016.

Spreadsheet tools are commonly used to track changes on farms, including changes to the land, crops, or animals. At Marsden Organic Farms two temporally sensitive items are tracked: crop locations in specific fields, and animal movement (Figure 4.11). It shows a spreadsheet used to track flowers grown in a specific field during the 2014 season. Each row in the spreadsheet represents an actual row in the field. Each year, the template is duplicated, instantiated with flower types, printed out, and annotated as the season progresses. This table-based representation is analogous to the map-based crop tracking at Brooks Organic Farms (Figure 4.10): both track the movement of crops across the farm over time.



FLOWER FIELD FALL 2014

FIELD

TP ON SOUTH SIDE
DS ON NORTH SIDE

	DATE	WHAT?	PLATES	NOTES
	Oct. 13th			
1				
2				
3				
4		Iris		
5		Iris		
6		Iris		
7		Shasta Daisies		
8	10/30	TP Fever few		12" spacing before the rain
9	10/30	TP Fever Few		
10	Oct. 14th	Godetia		
11		Godetia		
12		Godetia		
13		Godetia		
14		Godetia		
15		Snapdragons		
16		Snapdragons		
17		Snapdragons		
18		Snapdragons		
19		Snapdragons		
20		Snapdragons		
21		Snapdragons		
22		Snapdragons		
23		Godetia/Snapdragon/Sweet Williams		
24		Sweet Williams		
25		Ranunculus		
26		Ranunculus		
27		Ranunculus		
28		Ranunculus		
29		Ranunculus		
30		Ranunculus		
31		Ranunculus/Anenomes		
32		Anenomes		
33		Anenomes		
34		Anenomes		
35	11/5	Delphinium	TP	12" apart
36		Delphinium		
37		Campanula	1	
38		Campanula	3/4	12" apart
39				
40				
41				
42				
43				
44				
45	1/14	Aloha Rose/Bells		
46		Aloha Rose/Bells		

Figure 4.11: Representing space and time: Marsden Organic Farms, flower fields, 2014.

Animal movement at Marsden Organic Farms is similarly tracked (Figure 4.12). While it may seem like an innocuous activity, this log is instrumental to the farm maintaining its organic certification. While animals are only eating cover crop and crops that were not harvested, there is a requirement for no animals to have been in a field for 120 days before crops for human consumption can be grown organically [185]. This requirement makes it particularly hard for many farms to keep both animals and row crops.

Animal Tracking Log 2015

Date In	DATE OUT	Field ID	What they're eatting	CROP PLANTED	120 Day Ok	1st Harvest	Notes
1/7/15	1/18/15	XX lower South	Cover crop				Ninos, NW corner, moving W - E - W every 2 days
1/18/15	1/24/15	lower NE side	cover crop				Ninos, next to Asparagus, moving N - S every 2 days
1/24/15	2/2/15	XX upper	cover crop				Ninos, W side, moving N-S every 3 days
2/2/15	5/1/15	XX Orchard					Ninos
5/1/15	5/27/15	XX pasture	pasture/hay				Last batch of 2014 Ninos to superior + 8 new moms moved into Walnuts w/ ewes
6/4/15	6/16/15	XXPasture	pasture				2015 Ninos weened, moved thru pasture every 2 days
6/16/15	6/23/15	XX	cabbage, collards				Ninos, moving N - S
6/23/15	6/28/15	XX	chard				Ninos, moving S - N
6/28/15	7/20/15	Walnuts	clover				Ninos, E side middle, moving N then W then S
7/20/15	7/28/15	XXbottom South	cover crop				Ninos, W side moving W - E every 3 days
7/28/15	8/25/15	XX	melons				Ninos, started NW corner moving on a N - S, S - N zigzag thru entire field except for onions on E side. Moved every 2 days
8/25/15	9/4/15	XX Pasture	pasture				Ninos

Figure 4.12: Representing both space and time: Marsden Organic Farms, animal tracking Log, 2015.

4.4 Challenges, Restrictions, and Lessons

In this section, I articulate the findings of the study presented in this chapter as sets of: challenges in modeling small- to medium-scale sustainable agricultural systems, restrictions on the information management practices of farmers, lessons for design. In the subsequent chapter, I engage in responsive design work based on these these sets of challenges, restrictions, and lessons.

4.4.1 Challenges in Modeling Sustainable Agriculture

From the monoculture of almonds at the geographically distributed Iyer Orchards to the highly diversified and dynamic crop and livestock mix at Huang Integrated Aquafarms, the essential challenges farmers face when representing their systems involve capturing complexity, changeability, and context.

4.4.1.1 Capturing complexity

A consistent challenge across farms exists in representing variegated spatial complexity in terms of system composition and structure. In all the nut orchards, for example, alternating rows of trees within a single field contained different varieties for pollination purposes. Vertical integration of the farm, i.e., how much of the farm-to-table pipeline is integrated into the farm's scope of activities, plays a role in increasing the overall complexity of the farm. While some farms only grow crops or raise livestock, there are many others that we found processing, packaging, even trucking produce to consumers. The different layers of activity must also be considered: i.e., activities concerning the soil layer; the water and irrigation layer; the air and emissions; machinery and building infrastructure; the human layer; and not to forget, the crop layer itself. There is a tension between models that farmers use to create snapshots of their system in space (Figure 4.6), and those used to represent time (Figures 4.8 and 4.9). This tension has impelled farmers to create models to track changes in farm composition over time (Figures 4.10 and 4.11). How this inherent complexity of the farm is represented directly affects how it can be managed, modeled, and subsequently analyzed.

4.4.1.2 Capturing change

All farms encapsulate many time cycles. For example, staggered plantings of row crops like tomatoes are common to allow for a longer harvest period, resulting in several cycles associated with each planting overlapping. Yet more dynamism is introduced on farms containing multiple commodity types such as at Marsden Organic Farms. Due to changes occurring in a farm, models are also often out of sync with reality. This dynamic complexity on farms makes the representation of time, activities, and tracking changes a significant challenge. Farms are not only subject to human induced changes, but also at the whims of natural evolution and decay.

4.4.1.3 Capturing context

Farms do not exist in isolation. They have challenging and diverse relationships with their neighbors, society, and the natural environment. There are often interconnections between farms, whether it involves resource sharing, output or waste reuse (e.g. compost) or creating natural buffers between farms. These informal connections are rarely captured in farm models. The capture of context is challenging as farms have complex flows of resources within and among systems and subsystems. When assessing the environmental performance of farms, a further complication is that farm boundaries are fuzzy; where does the farm end and the natural environment begin?

4.4.2 Restrictions on Information Management Practices

4.4.2.1 Restrictions imposed by environmental policy & certifications

Many policies and certifications require data to be both collected and structured using specific forms, formats, or tools. While these may be useful in providing novice farmers with a starting point as to how to even begin putting together information regarding environmental, resource, and operational data, most of the farmers we spoke with end up restructuring their previously collected data to fit policy and/or certification requirements.

4.4.2.2 Restrictions imposed by the human and social context

The population of farm workers includes a large Spanish speaking population and a diverse range of literacy levels [155], as well as a varied set of communication needs across stakeholders. Such diversity is not always accommodated. Models (e.g., Figure 5) may include multiple languages or a visual focus to overcome barriers to communication in the social context of the farm.

4.4.2.3 Restrictions imposed by the mismatch between systems, models, and tools

There is a lack of consistency and technological capacity across the spectrum of sustainable agriculture as a result of the sparse attention that has been paid to the information management needs and requirements of sustainable farmers. Their agricultural systems cannot be adequately represented and analyzed using current modeling tools and methods, and many environmental data sources have not been designed to integrate with the toolkits that such farmers currently use.

4.4.3 Lessons for Design

4.4.3.1 Lesson 1. Models must integrate disparate data structures

Artifact trails spanned across disparate data structures: from hand-drawn maps containing crop locations, spreadsheets varying in structure from year to year even within a farm, to custom databases to handle portions of the farmer's workflow. Maintaining coherence and consistency across data structures is key to stitching together the information workflow of sustainable farmers; the heterogeneity of data structures within farms provides a significant stumbling block in effective workflows.

One potential avenue for future work involves the design of better models to encapsulate the types of data that are collected and fit with the data collection techniques that farmers engage in. Models are apt devices for communication of a system's composition and performance, as well as useful artifacts for reflection [14]. In particular, a domain-specific modeling language would enable system stakeholders to gain perspective on their systems, perform environmental analyses, and create abstract yet grounded models that they can manipulate before changing the real world systems that are represented.

4.4.3.2 Lesson 2. Models must accommodate disparate mediums of technology

The switching between data structures is accompanied by several transitions between different mediums of technology, resulting in a messy information management experience. Five genres of technology were used across one or more farms: physical or paper-based artifacts; communication technologies like email; external regulation- or certification-specific software; farm-specific custom software; and office productivity software such as Microsoft Word and Excel.

An integrated computational platform compatible with, or at least evolvable from, the farmer's current toolkit is needed. To create an ideal information management experience, such a platform must scaffold existing farmer data collection practices and be interoperable with the genres of technology already in use.

4.4.3.3 Lesson 3. Models must support varying abstraction, formality, and granularity

Farm models varied in level of abstraction, formality, and granularity, both within an individual farm and across agricultural system types. For example, on some farms, resource use was tracked at the whole farm level, while on others there were intricate interconnections between subsystems requiring tracking at a granular level. The commodity and process complexity of the farm also affected the level of abstraction, formality, and granularity of models.

Models need to be flexible enough to capture whole-farm activities as well as fine-grained data about specific farm components. Ideally, farmers should be able to create both informal and formal models depending on the type of data they have and analyses they plan to conduct. Consequentially, relevant tooling must be capable of representing the varying spatial and temporal complexity present throughout the spectrum of sustainable agriculture.

4.4.3.4 Lesson 4. Models must enable reusability

Many of the models used for internal assessments by farmers are created in an ad hoc manner and for a specific purpose For example, a map created for communication to visitors may be opportunistically used for coordination among farmworkers. However, this is a one-off reuse, and is not inherently supported by the models. Representations cannot always be easily repurposed, resulting in a significant reusability gap.

Further, data is often isolated in purpose-specific models. For example, input logs used to track resource application for organic certification are not necessarily connected to inventories that are used to track expenditure on materials. Data and effort are duplicated as data is tracked separately for inventory management and organic certification. Farm data needs to be captured in a general enough form such that it can be manipulated and transformed on demand.

There is an opportunity to reduce the reusability gap by enabling farmers to create modular component-based farm models. There is also a significant amount of publicly available environmental data, such as data on soil composition throughout the United States [244], global weather data [156], and California-wide water quality and availability [218]. These data can and should be incorporated into information management tools for sustainable farmers to reduce their data collection burden.

4.4.3.5 Lesson 5. Models must allow for the tracking of change

The transience of agriculture means that not all data collected is necessarily archived. This is further exacerbated by the rate of change on farms: the more often the farm changes, the easier it needs to be to update the model. This also affects the formality and reusability of farm models.

Use of model configuration management may allow for farmers to track changes in their farm models just as they use models to track changes in their farms. This would also allow farmers to compare models over time and reduce the effort involved in updating models to reflect changes. We found workarounds implemented by farmers to mimic such a workflow. By designing with the intent to archive historical data and track changes, the inherent dynamism of the farm can be captured.

4.4.3.6 Lesson 6. Models must support varied data collection goals and causes

There is a mismatch between the causes and goals of data collection, particularly as the farm evolves. While initial causes for data collection may be for regulatory reporting and system understanding, eventually farmer goals can expand to include communicating to diverse stakeholders (from the consumer to the farm worker), environmental analyses, and monitoring. The mismatch between the collection trigger and emergent goals results in a lack of coherence in farm models and data workflows.

We must explicitly consider both the causes and goals of data collection in the design of information management tools for sustainable farmers to ensure that appropriate data is aggregated and connected. Supporting easy transformation of the information management structures and practices would facilitate synchronicity among causes and goals.

4.4.3.7 Lesson 7. Models must support coordination and collaboration

Farm stakeholders are constantly using, sharing, and communicating various data for daily decision-making and problem solving. However, many of the technologies we found in use were not designed to meet the coordination and collaboration needs of varying farm stakeholders.

Any redesign of the information workflow of sustainable farmers must provide these stakeholders with the capacity to conduct environmental assessments and other forms of analysis; coordinate among farm workers and other stakeholders; and communicate with regulators, certifiers, and consumers as needed. Explicit attention to the differing privacy and access characteristics of data would be critical.

Chapter 5

Modeling Sustainable Systems

> *The purpose of [...] a model is to provide efficient and convenient access to information about the world. By capturing states and events of the world and using them to build and maintain the model we provide ourselves with a stored information asset that we can exploit later when information is needed but would be harder or more expensive to acquire directly.*
>
> — Michael Jackson, The world and the machine [116].

In this dissertation, I have argued that farms are complex adaptive systems [110, 150]. Farms can also be characterized as socio-environmental systems [154], and more recently, socio-technical systems [122]. They can be characterized in many different ways, but the core of each of these characterizations is that farms are complex and dynamic, with many interactions among the subsystems within them, and many interdependencies with systems outside of them.

Farms are systems and the challenge of modeling farms is one of aptly modeling systems. There are two further challenges that arise when modeling sustainable agriculture: modeling sustainability as a multidimensional and fuzzy concept, and modeling the breadth and variety of agricultural data.

The balance between modeling systems, modeling agricultural systems, and modeling sustainability results in a "Goldilocks" [198] design challenge: the final design must not be too general, nor too specific; not too simplified, yet able to express the complexity of farms. It has to be *just right*.

Every farm is unique. Between the farmers, local geography, microclimates, mix of crops cultivated, and agricultural activities, it is vital that any designed artifacts are flexible. There is an inherent danger in resorting to a one size fits all solution. The *Goldilocks point*, that is, the point at which a solution is *just right*, should be a movable point within a range. To address the *Goldilocks* challenge of modeling sustainable agriculture, I engaged in an iterative design process involving both consistent reflection on farm data and gradual refinement of the designed artifacts. By engaging in the theoretical sensitivity[1] [53], I seed the design activities of this dissertation in the context of sustainable agriculture.

The motivating design prompts (as identified in Chapter 4) are:

1. How can we reconcile the different kinds of farm data that are collected, varying reasons for data collection, the varying forms of representation, and the different stakeholder requirements, to create a coherent model of a sustainable agricultural system?
2. Further, how can we use these models to reflect on the environmental performance of the agricultural system of interest?

Fundamental design requirements (as listed in Chapter 3) are:

- Abstraction: A well-structured object model to represent the system.

[1]A means for considering the factors that affect the construction of a grounded theory [53].

- Composition: Objects groups as components that represent subsystems.
- Modularity: Distinct interfaces between components allow for a modular system model.
- Granularity: Support for describing the system at varying levels of granularity.
- Adaptability: Support for capturing information regarding object and system changes.

Chapter Overview: In this chapter, I present **MoSS**: a framework to enable the **Mo**deling of **S**ustainable **S**ystems. I detail the design methodology that led to MoSS in Section 5.1. In Sections 5.2 and 5.4, parts of the MoSS framework are specified, with a brief demonstrative case study in Section 5.5. Finally a set of heuristics for using MoSS are laid out in Section 5.7. MoSS is subsequently evaluated in the next chapter.

5.1 Methodology

Figure 5.1 describes the overarching design process that resulted in the MoSS framework. Each of the design activities and iterations are describe in this section.

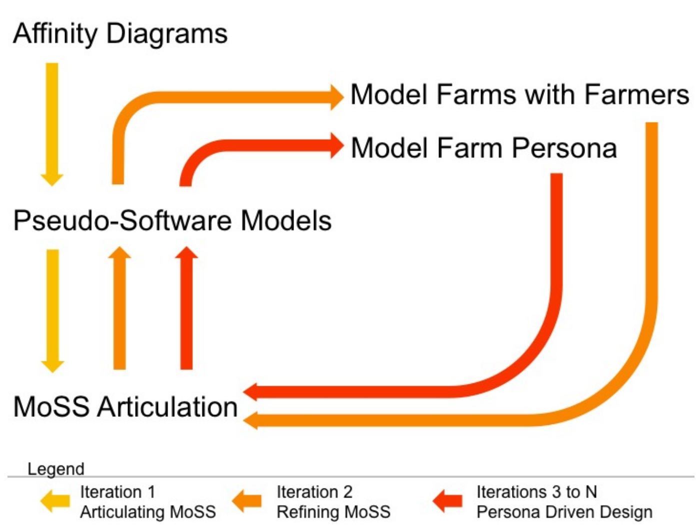


Figure 5.1: The MoSS design process.

5.1.1 Iteration One: Articulating MoSS

The first design iteration, shown in Figure 5.2, involved three linearly conducted activities: affinity diagramming, creation of Pseudo-Software Models, and the articulation of the first version of MoSS.

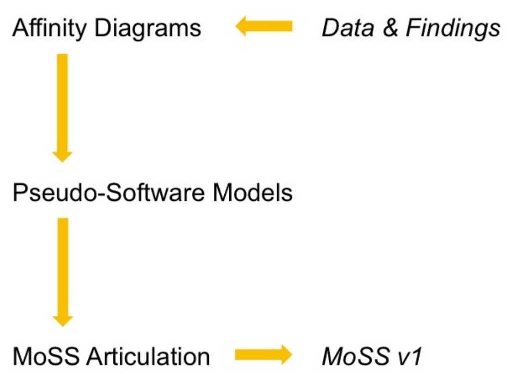


Figure 5.2: The MoSS design process: Iteration one, articulating MoSS.

Affinity Diagrams: The design of MoSS is based on data and findings regarding formal modeling in agriculture (Points 1-3 in the list below) and information management in small- to medium-scale sustainable agriculture in California (Points 4-6 in the list below). These were described in Chapters 3 and 4 respectively, and are briefly summarized as follows:

1. Data: Formal modeling methods, data, and tools used in the assessment of agriculture.

2. Findings: Observations regarding life cycle assessment in agriculture.

3. Findings: Essential difficulties in the formal modeling of sustainable agriculture.

4. Data: Farm interviews and farm data artifacts.

5. Findings: Categories and types of representation of farm data.

6. Findings: Challenges, restrictions, and lessons for design for sustainable agriculture.

These data and findings seeded the first design iteration of MoSS. First, I revisited the original codes that were created during the GTM analysis of the farm data and artifacts. Then, I created affinity diagrams [24] to sort out the codes to elicit, for example:

- Clusters of related data,
- Relationships between different clusters of data,
- Rationale for why data was collected, as well as eventual use, and
- Gaps in farmer-goals and data-available.

A sample *Affinity Diagram* is shown in Figure 5.3.

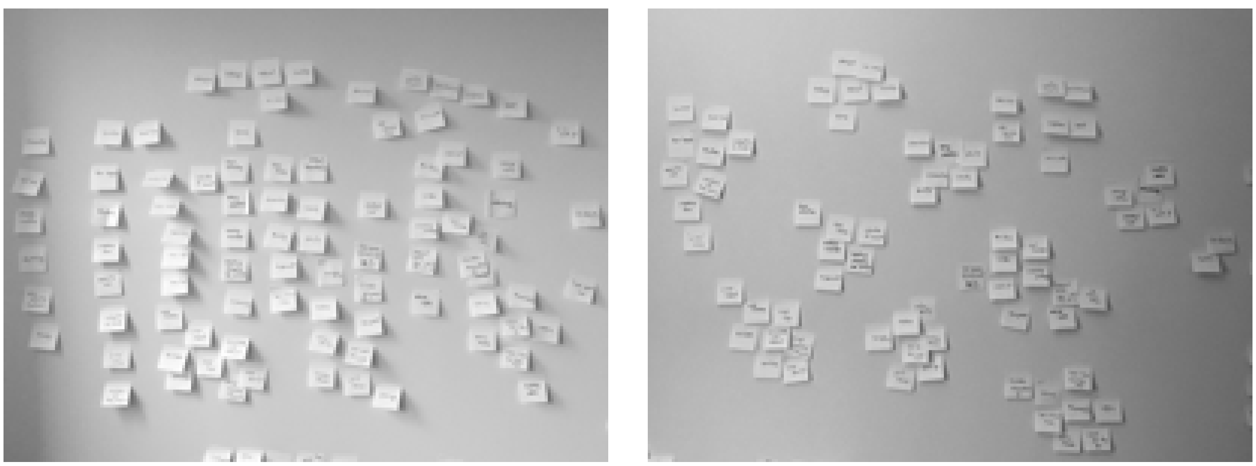


Figure 5.3: Sample affinity diagramming activity.

Pseudo-Software Models: The result of each affinity diagramming exercise was subsequently modeled as a Pseudo-Software Model. Groups of codes were merged to form objects, which were then further connected to form hierarchies of types, and part-whole relationships. Using Visual Paradigm [247], object diagrams [192] were created to represent the affinity diagrams. Through this process, a sea of concepts was distilled into an initial model.

MoSS articulation: Finally, these models were collectively articulated as the MoSS framework consisting of elements, relationships, and structures.

5.1.2 Iteration Two: Refining MoSS

After creating the first major version of MoSS, I designed a preliminary evaluation study in the form of a modeling activity, intended to test the first version of MoSS and guide subsequent refinements. Figure 5.4 overviews the activities within this iteration.

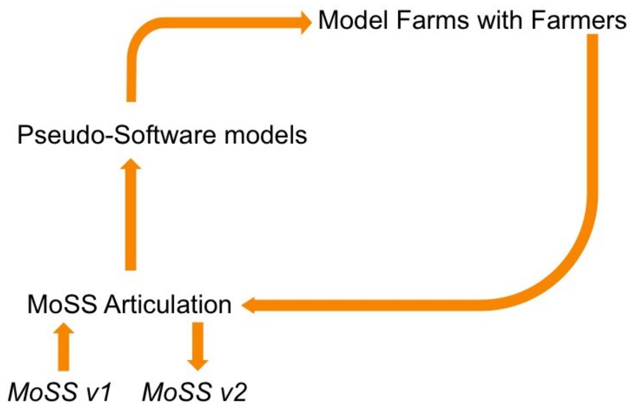


Figure 5.4: The MoSS design process: Iteration two, refining MoSS.

Modeling Farms with Farmers: The motivating question for this preliminary evaluation study was:

> Does MoSS adequately enable a (small- to medium-scale sustainability-oriented) farmer to create a farm model representing environmental performance?

The modeling activity utilized a physical pseudo-interface prototype to create a farm model. The prototype was a pseudo-interface as it was not intended to be a physical analog for an actual modeling tool, but instead a canvas or template for the farmer to lay out parts of their farm model onto. The goal of this activity was to explore the capacity of MoSS model elements, not to test a user interface.

Figure 5.5 demonstrates the initial *board* setup, some of the MoSS *element cards*, and two *legend guides*. The annotations on the figure reflect the setup and explanation that was provided to participants before we began the modeling activity.

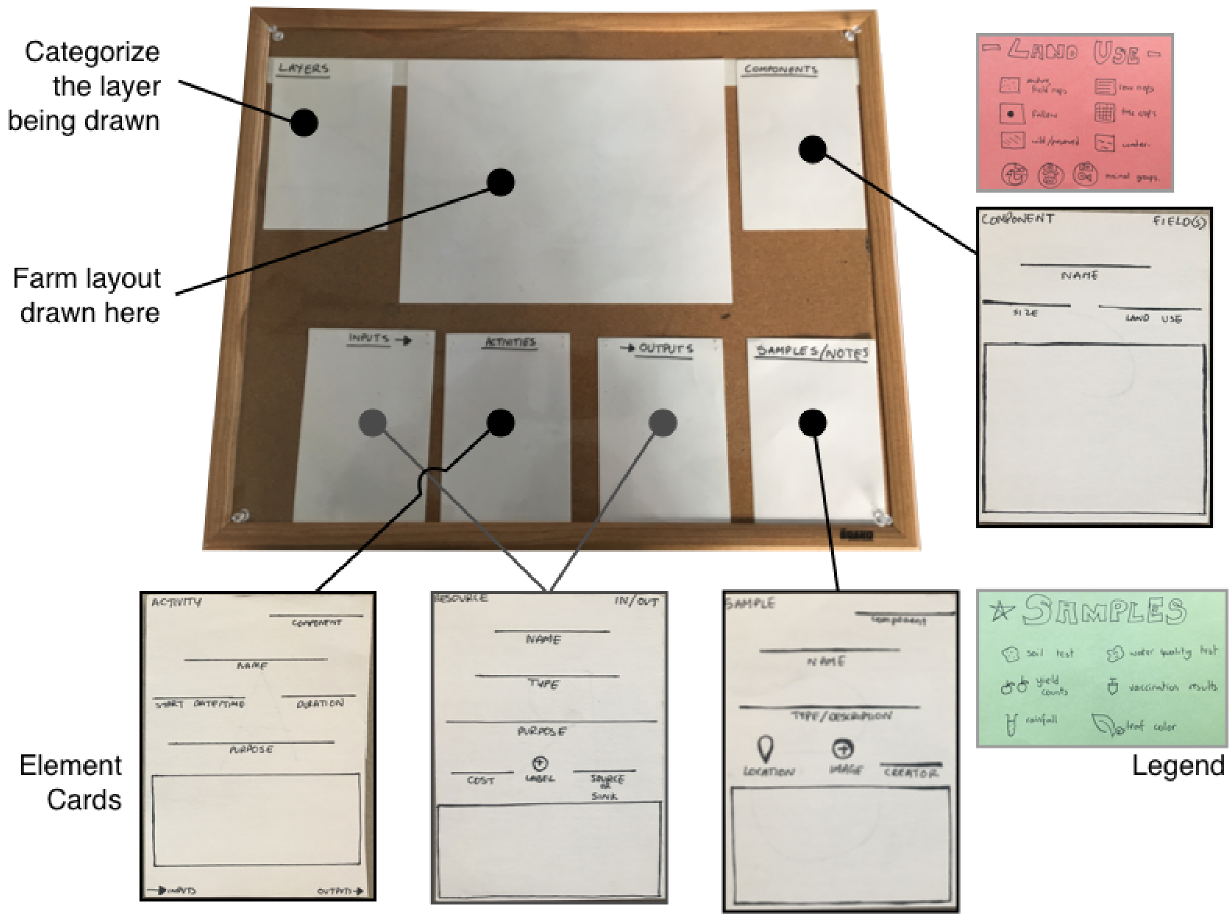


Figure 5.5: MoSS modeling activity setup.

The prototype consisted of three physical parts and a set of prompts:

1. *Board*: A cork-board that acted as the interface boundary on which objects could be placed and drawn. This was overlaid with a transparency to allow the participant to

draw directly on it. Underneath the transparency were rectangular pieces of paper to create discrete areas for specific types of information.

2. *Element Cards*: A set of fillable cards were created to contain information about various aspects of the farm. Each card represented a MoSS element, as described by the first Pseudo-Software Models, and instantiated in the domain of agriculture.

3. *Legend Guides*: A small selection of suggested icons and groups of information were created to kick off certain modeling prompts. These were created to try to reduce the cognitive load of having to come up with icons and to guide the participant in case they got stuck.

4. *Modeling Prompts*: A selection of prompts were written to initiate a modeling activity. These were intended to reflect the kinds of triggers for farm data collection. These prompts were based on the findings of Chapter 4. However, due to the brevity of the activity, all participants primarily engaged with Prompt 1 (*What does your farm look like?*), occasionally getting to Prompt 2 (*Let's pick a field. What is going on this field?*), and Prompt 3 (*What environmental sustainability issues are related to [some level]?*). Each prompt was designed to take about 15 minutes to respond to, thus allowing for a modular study design.

Recruitment: In January 2017, I attended a conference on sustainable agriculture in California with the goal of meeting with previously interviewed farmers (for the study described in Chapter 4), as well as to recruit new participants for the modeling activity during breaks and other unstructured sessions. Unfortunately, due to the hectic nature of conferences, I was only able to recruit six participants, for very limited and varying session lengths, which resulted in minimal system models and varying detail regarding farm activities. In two cases, data collected had to be discarded as:

1. The discussion veered toward general feedback on the modeling activity and more general conversation regarding challenges and opportunities in sustainable agriculture. The modeling activity was thus begun, but not completed.

2. The person interviewed was not a farmer, but a cultivation equipment manufacturer.

A brief overview of the 4 valid participants of this study is shown in Table 5.1 below. None of these farmers were involved in study described in Chapter 4: they had no prior exposure to the work that led to the development of MoSS.

Table 5.1: Summary of farms participating in evaluation study.

Codename	Farm Description
Avery Farms	Diverse and integrated farming operation, including a permaculture orchard, livestock, and vineyards. The farm also runs an educational program, hosting farming interns on site.
Bezier Orchards	Organic citrus orchard.
Chuck Orchards	Biodynamic farm apple orchards, cider making operation, and livestock.
Dancer Farms	Diverse and integrated farming operation, including small livestock (e.g., goats), and a variety seasonal crops grown for a CSA program. The farm's main barn also doubles as an event space.

Findings: Figure 5.6 (page 131) shows the four farm models created each of the farmers interviewed.

Major observations as a result of each of these modeling activities with the farmers were:

1. The layer metaphor did not work as anticipated. Layers primarily worked for representing physical farm layouts, and were not used for temporal representations.

2. Selective granularity allowed for creation of *quick and dirty* models. These partial system models often focused on one or two specific aspects of the farm.

3. More unstructured than structured data was modeled.

4. Component-activity-resource relationships worked as anticipated.

5. The ability to attach data to any and every element was found to be useful.

6. All farmers began with the farm layout, though the option to begin with the activity schedule was offered. Each modeling workflow followed a similar pattern: layout first, activity next, augment layout, model next activity... and so on.

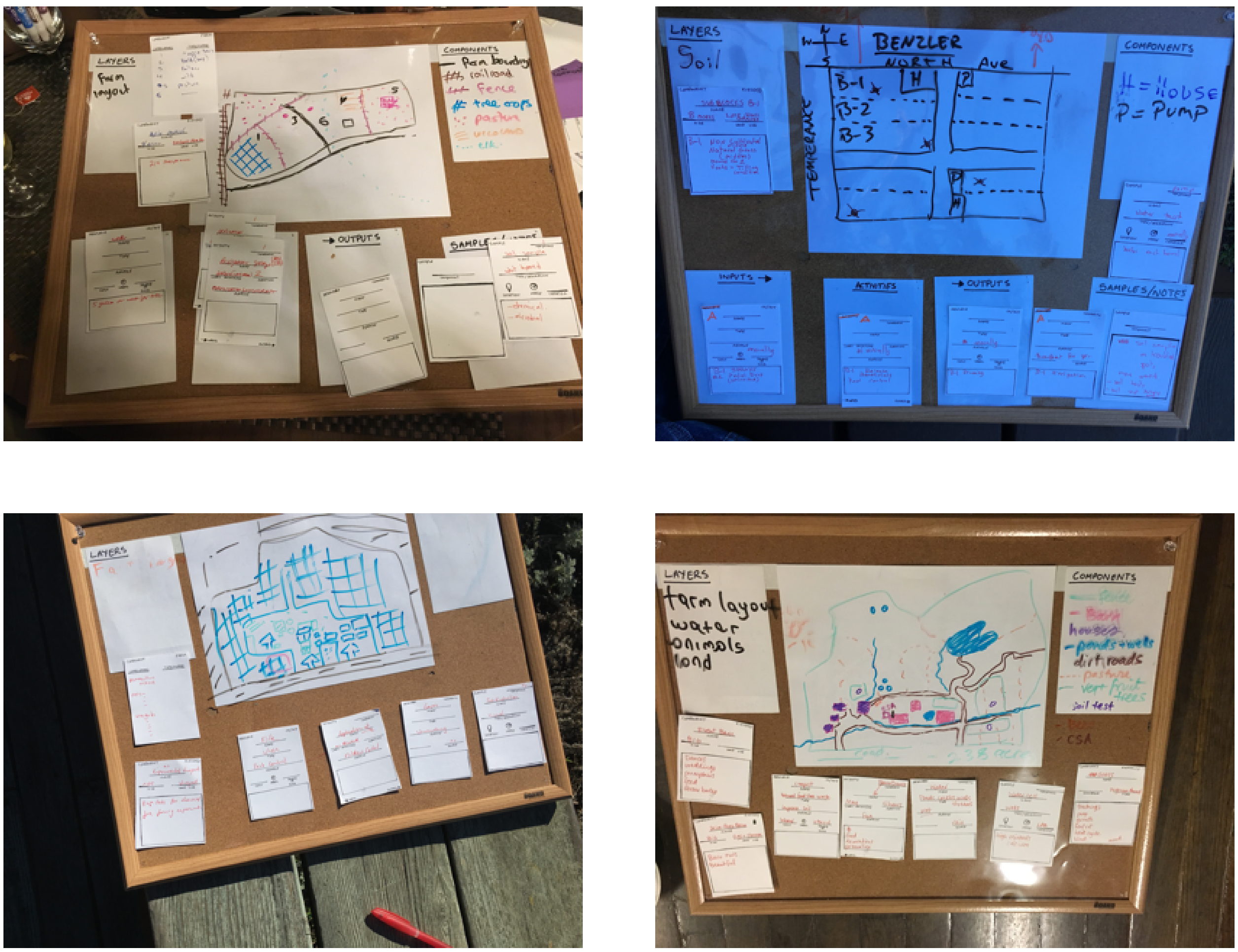


Figure 5.6: Farm models created by farmers. *Clockwise from top left:*
(1) Avery Farms
(2) Bezier Orchards
(3) Chuck Orchards
(4) Dancer Farms.

MoSS Articulation: This findings of the modeling activities with farmers resulted in an increase in the domain-specificity of MoSS, the introduction and deprecation of various MoSS elements, a new abstract model, and subsequently, a new version of MoSS.

Moving Forward: The discussions with the farmers during the modeling activity were valuable and the lessons learned directly influenced the design of MoSS. However, two primary challenges, recruitment difficulties and time constraints, limited this activity. Further, the opportunity to conduct the modeling activity was more fortuitous than planned; setting up a whole new set of evaluation activities would have required a larger study design, with more vigorous recruiting, such as that of the qualitative study described in Chapter 4.

5.1.3 Iteration Three: Persona Driven Design

The majority of the design iterations involved: refining the Pseudo-Software Models, modeling a set of Farm Personas, and finally re-articulating MoSS. This process is shown in Figure 5.7.

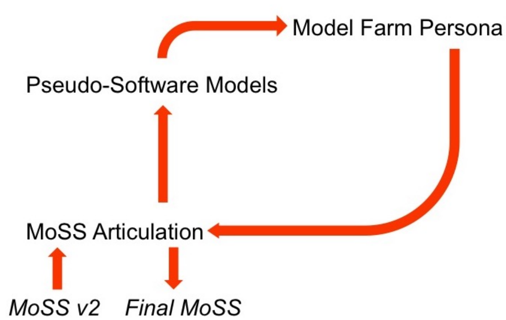


Figure 5.7: The MoSS design process: Iteration three, Persona Driven Design of MoSS.

Farm Personas: Personas typically describe representative users of a particular software system [51]. They have been used in software design as stand-ins for real users, allowing people to engage in human-centered design, where the user experience and interaction of the human with the system is the key focus [175].

In this dissertation, I flip the traditional persona, and instead use it to describe a system (the farm), that a human (the farmer), is interacting with, the result of which is a *Farm Persona*. These Farm Personas were created based on the data and findings of Chapters 3 and 4. Methodological detail on the design of these personas is available in Section 6.1 of Chapter 6, as the Farm Personas are explicitly presented during the evaluation of MoSS.

The Farm Personas were used to engage in *Persona Driven Design*. Partial MoSS models were created to represent various activities, components, and aspects of hypothetical farms. These models were then used to refine the *Pseudo-Software Models* and thus refine MoSS. For example, Figure 5.8 (page 133) below shows how a Farm Persona called *Blackbird Gardens* was used to explore the representation of crop layout and field management. Persona Driven Design thereby allowed for the farm-centered design of MoSS.

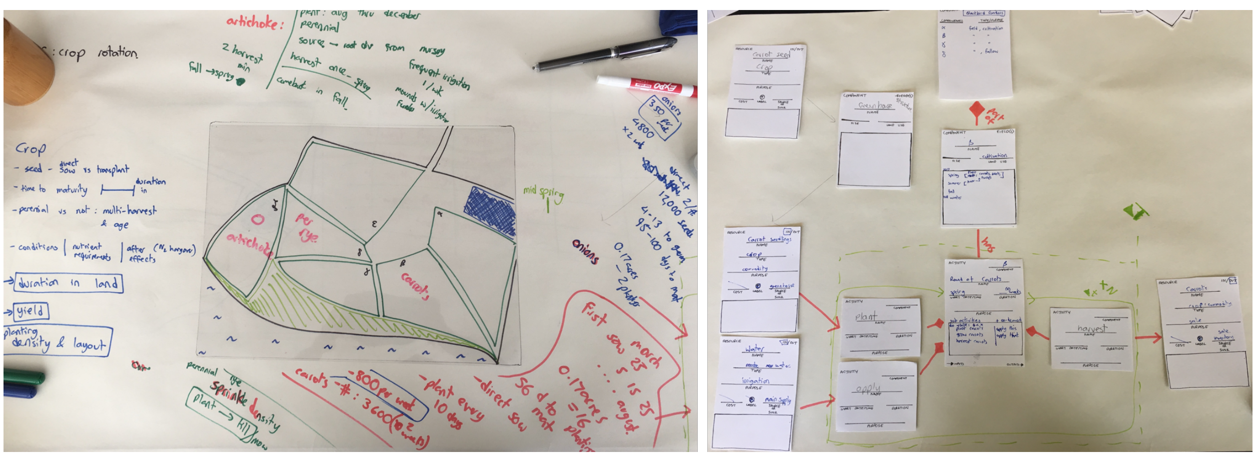


Figure 5.8: Blackbird Gardens in action. *Left:* Exploring crop layout. *Right:* Using MoSS element cards to explore crop planting and input schedules.

MoSS Articulation In the last design iteration as part of my dissertation research, the *MoSS Articulation* activity involved the finalization of the MoSS grammar, visual notation, modeling heuristics, and preliminary model checking mechanisms.

5.2 The MoSS Framework

MoSS is a framework to enable the **Mo**deling of **S**ustainable **S**ystems. In this section, I briefly describe three dimensions of a system as treated in MoSS.

Consider first, a system such as a farm. A simplified farm diagram is shown in Figure 5.9. A farm consists of natural and human-made objects, land, air, and water, exists within a local environment, contains subsystems, and supports life. *MoSS supports the representation of the physical structure of a system — the spatial dimension.*

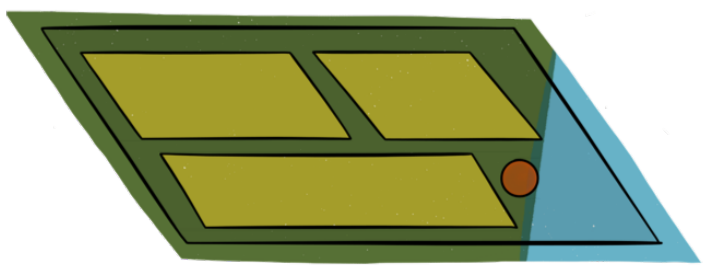


Figure 5.9: A simplified riverside farm layout, with three fields (light green rectangles), and a house (red circle).

This system is changing over time. Fields are created, cultivated, and harvested. Boundaries are built and moved. Riverbanks swell and the soil composition underfoot varies. *MoSS supports the representation of system changes over time — the temporal dimension of a system.* Figure 5.10 shows a simplified timeline consisting of six snapshots of a farm as fields are cultivated and thereby added to a farming operation.

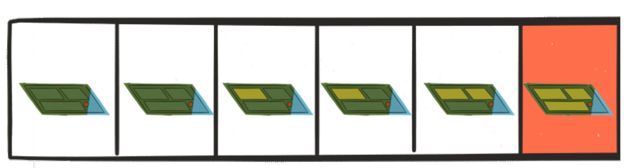


Figure 5.10: Fields are cultivated (light green rectangles) and added thus to the farming operation, as shown in each simplified annual snapshot.

We can observe, sample, measure, write down, or otherwise collect data about various aspects of this system in the world. Each datapoint has both a spatial and temporal scope. *MoSS supports the representation of information about a system.* As marked on Figure 5.11, farm data can regarding:

1. A specific point in space at a point in time.
2. The system as a whole during a particular point in time.
3. A subcomponent of the system at a particular point in time.
4. System behavior over a period of time.
5. A potential system configuration at some time in the future.
6. A specific input entering the system.

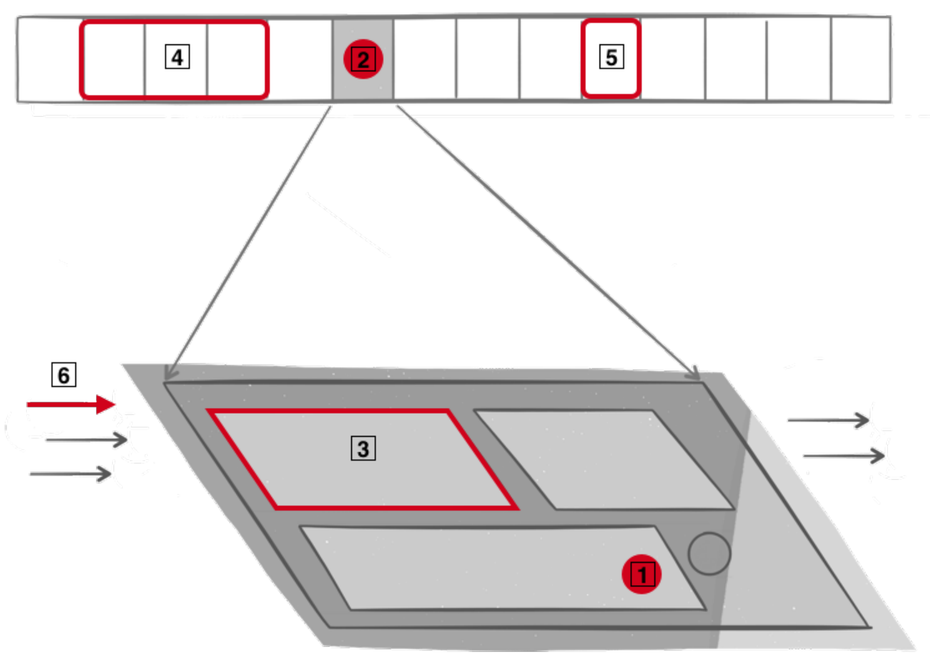


Figure 5.11: Farm data can be scoped at various levels of specificity.

The goal of MoSS is to capture the spatial and temporal dimensions of a system in a single model that can be manipulated, filtered, and analyzed to explore the sustainability of the system. *MoSS supports the representation of information about about a system in the world as it changes over time.*

Figure 5.12 combines the spatial (Figure 5.10) and temporal (Figure 5.10) dimensions in which data are collected (Figure 5.11), providing an abstract view of a system according to MoSS.

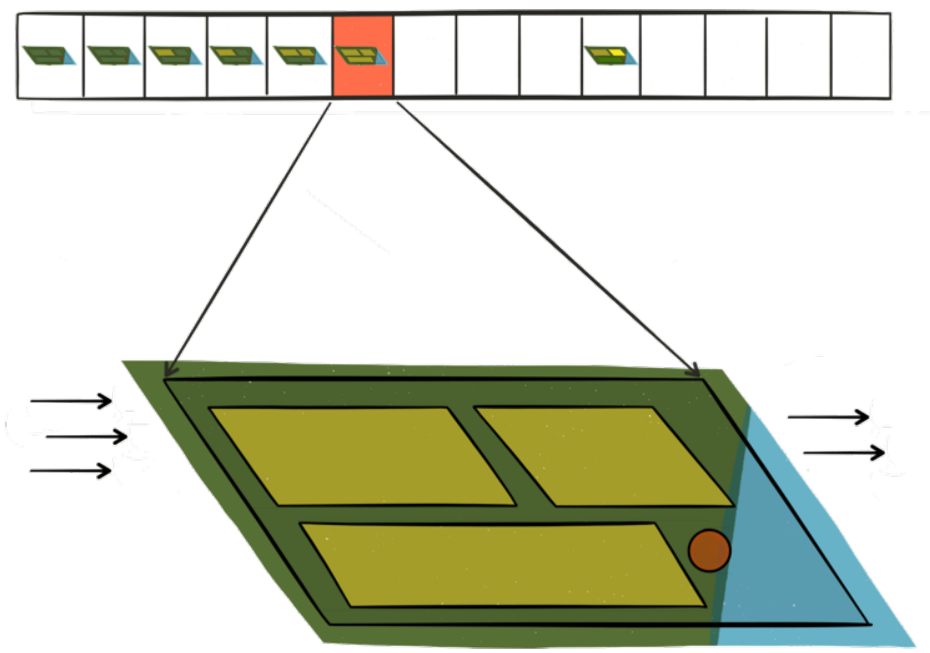


Figure 5.12: A system in the world according to MoSS.

The various elements that make up the MoSS framework are based on this abstraction of systems in the world. The rest of this chapter will focus on describing the MoSS framework as creating using a farm-centered design process.

5.2.1 MoSS Overview

The MoSS framework consists of three parts:

1. *An Abstract Model:* The MoSS Abstract Model, described in Section 5.3, contains the fundamental elements required to represent a system.
2. *Domain-Specific Elements:* The Abstract Model is then instantiated in the domain of sustainable agriculture. The Domain-Specific Elements are described in Section 5.4.
3. *Perspectives:* Finally, Perspectives allow for the filtering and checking of a MoSS model against specific conditions. This allows for selective exploration of a system model. Types of Perspectives are described in Section 5.6.

To support the use of the MoSS framework, there are two ancillary parts:

1. *MoSS Grammar:* A common grammar is described in Section 5.2.2 to provide consistency across MoSS models.
2. *MoSS Heuristics:* A set of heuristics are described in Section 5.7 to guide the creation of MoSS models.

5.2.2 MoSS Grammar

The grammar and visual notation of MoSS are based on those commonly found in Object Oriented Modeling, and can be thought of as a UML-variant. MoSS uses a simplified set of relationships, objects, and diagrams. From here on, the following notation will be used when representing systems using MoSS.

Element: An element represents related attributes of the system to be modeled. It is the most generic MoSS object. Elements are written in lower camelcase, monospace, font: `mossElement`.

A set of abstract and domain-specific elements are detailed in Sections 5.3, and 5.4. All MoSS `elements` are symbolized by a box, where attributes can be specified as shown in Figure 5.13.

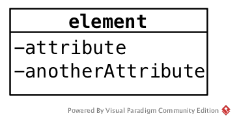


Figure 5.13: A MoSS `element`.

Similarly, the text equivalent is: `mossElement [attribute, anotherAttribute]`

Instance: An instance is a specific element of a specific system in the real world to be modeled. Instances are written in small capitals, in a monospace font: `INSTANCE`. As a MoSS instance is of a particular element type, a colon is used to denote this relationship: `mossElement:AN INSTANCE`.

The first use of a MoSS Instance is seen in Section 5.5, a case study showing MoSS applied to a 1-acre tomato farm. An `INSTANCE` can be specified in the MoSS box as shown in Figure 5.14.

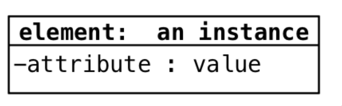


Figure 5.14: A MoSS `INSTANCE`.

Once again, the text equivalent is: `mossElement:AN INSTANCE [attribute:VALUE]`.

Relationships: Five types of relationships are possible between MoSS Elements: association, constraint, inheritance, composition, and utilization/production. These are shown in Figure 5.15. The textual equivalent of these relationships is shown in Table 5.2.

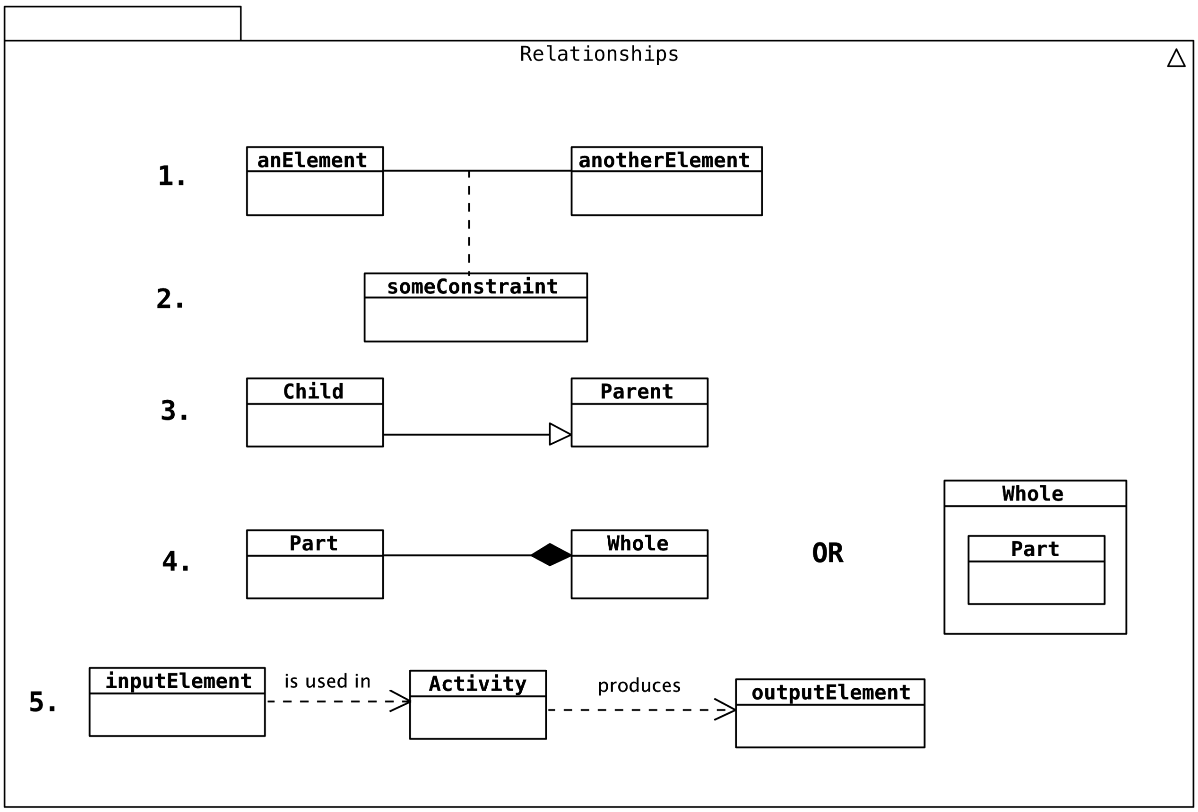


Figure 5.15: Visual notation for MoSS relationships, See also: Figure 5.2.

Table 5.2: Text notation for MoSS relationships, See also: Figure 5.15.

Ref.	Relationship	Text
1	Association	`anElement — anotherElement`
2	Constraint	`(anElement — anotherElement) | someConstraint`
3	Inheritance	`Parent.Child`
4	Composition	`Whole/Part`
5	Utilization/Production	`resourceInput -> Activity -> ResourceOutput`

Specificity: MoSS Elements are written, left to right, from less to more specific, and from abstract to domain-specific. A period is used to connect MoSS elements to denote increasing specificity.`abstractElement.domainSpecificElement: AN INSTANCE`.

This notation is used in the writing of this chapter to differentiate, for example, the use of the word *component* as part of a sentence versus a `system` consisting of `components` i.e., the MoSS declaration `system/components`.

5.3 MoSS Abstract Elements

A `system` consists of two basic elements: `components` and `activities`. A `system` is in itself a type of `component`. A `resource` is a type of `component` that is used and/or produced by an `activity.data` can be associated with each of these four elements.

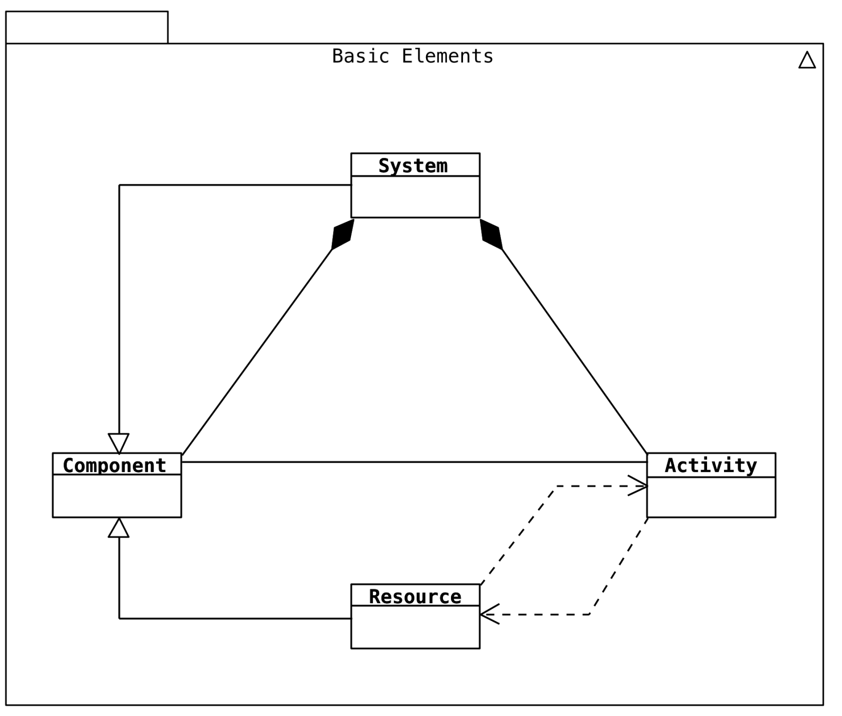


Figure 5.16: MoSS abstract model: Basic elements.

5.3.1 `components`

A `component` can represent any physical object in the real world. A `component` is a point, or group of points, that exists in space. Examples of `components` include: a field, a truckload of coal, a fence, a group of vines, a sack of potatoes. A `component` can be made up of other `components`. Figure 5.17 shows the basic MoSS components, their relationships, and supporting elements.

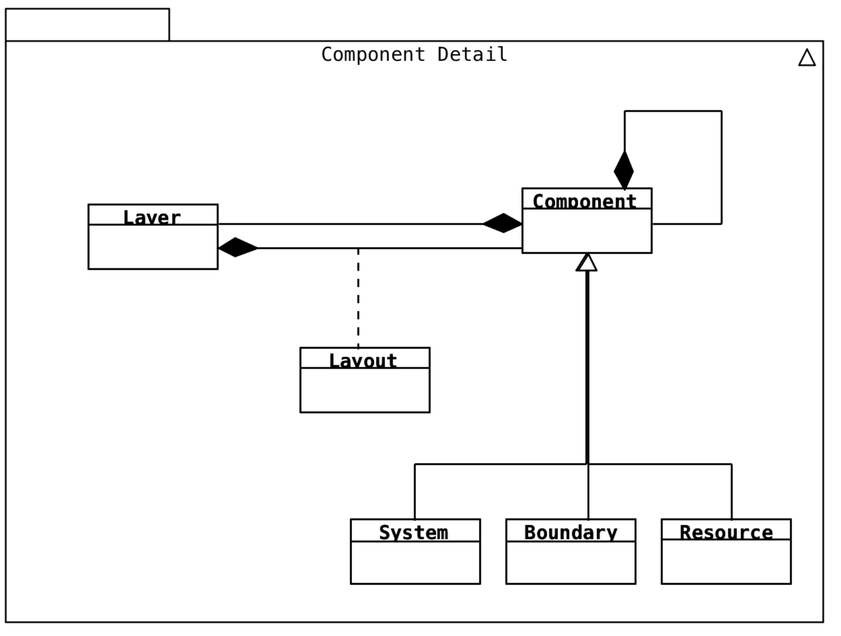


Figure 5.17: MoSS abstract model: `component` detail.

A `system` is a special type of `component` that represents the system of interest as a whole: it is the root element. One could argue that when modeling a system in the world, a `system` is a `component` that is technically a part of the larger `system:WORLD`. However, a good model is scoped to allow the modeler to gain particular insights into their system of interest [135], therefore we need not model the world. Instead, we use `system` to contain the entire system model. Similarly, a `boundary` is a special type of component that spatially constrains an associated `component`.

A component can have many layers. A layer is a group of related components. It can, therefore, be used to describe nested components or components located within a spatial boundary. A layout can be specified to determine how these components are arranged within a layer. For example, a layout can be defined to arrange elements according to a grid pattern with a regular spacing.

5.3.2 activity

An activity is any process in the real world that occurs over time. An activity is created by the mere passage of time. activities can be human-induced or natural, and can involve the consumption and/or production of one or more resources. Examples of activities include: harvesting tomatoes, payment of a salary, building a shed, consumption of water, making wine, decaying waste. Figure 5.18 shows the basic MoSS activities, their relationships, and supporting elements.

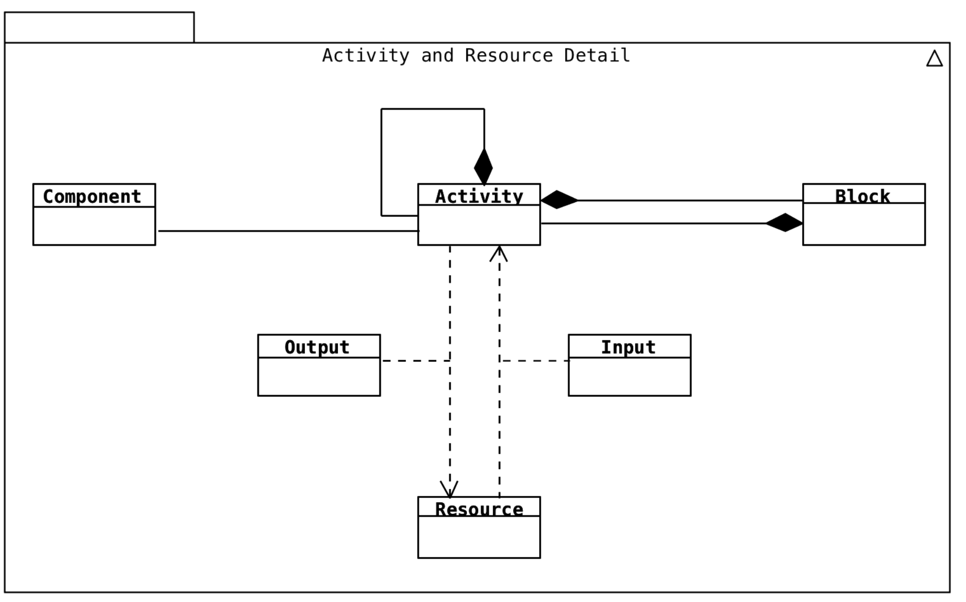


Figure 5.18: MoSS abstract model: activity and resource detail.

`activities` are constrained by temporal boundaries, specified as a duration of time with a beginning and, if known, an endpoint in time. An `activity` can be made up of other `activities`. `activities` occur within a particular `component`, and are therefore always associated with at least one `component`, whether the `system` itself, or some constituent `component`. `activities` involve the consumption, production, processing, or otherwise manipulation of `resources`.

A `block` is a group of `activities` occurring within a specific time period, describing, for example, concurrent or colocated `activities`. `activities` are arranged in chronological order within a `block`.

5.3.3 `resources`

`resources` are materials or energy in the real world that are used or produced during an `activity`. Examples of `resources` include: calories, money, plastic tubes, water, oranges.

When a `resource` is an input to an `activity`, the point of origin can be specified as the `input[source]`. This could be an external `system` or some `component` within the current `system` being modeled. Further, the time of use can be specified as the `input[timestamp]`.

`resources` can be an output of an `activity`, whether intentional, waste, or otherwise. The destination of this `resource` can be specified as the `output[sink]`, and the time at which it exits the `activity` is the `output[timestamp]`. If an `activity` has many `inputs` associated with it, one can infer the time at which the `activity` began by checking when the first `input` was associated with the `activity`. Similarly, the end time of the `activity` may be inferred based on the time at which the last `output` associated with the `activity` exits. A `resource`'s provenance can be also determined based on the chain of `activities` that use and produce it.

5.3.4 `data`

Knowledge about the real world can be represented in the form of `data` associated with the MoSS `element` of interest. These range from qualitative observations to quantitative measures. `data` can be both structured and unstructured. Examples of `data` include: soil moisture on a field, how many hours it took a person to pick all the tomatoes, where the wood for the fence came from, the water quality of the water used to irrigate the vines.

5.3.5 MoSS Abstract Model

The MoSS Abstract Model consists of each of the elements presented in this section, as shown in Figure 5.19.

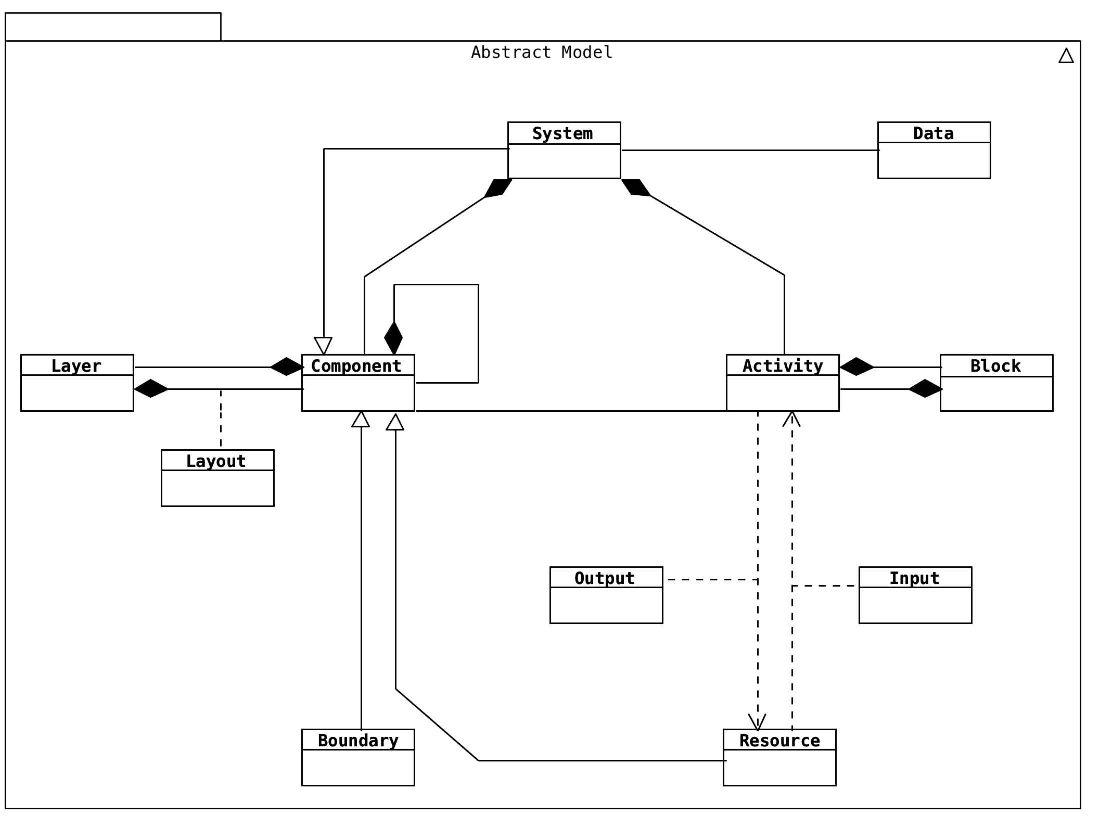


Figure 5.19: MoSS abstract model.

5.4 MoSS in Agriculture: Domain Specific Elements

To enable the modeling of systems in the domain of sustainable agriculture, the abstract model must be instantiated using domain-specific elements. When considering MoSS in Agriculture, I specify elements to model crop cultivation and environmental sustainability in small- to medium- scale farms.

The economic, human, and social sustainability dimensions of a farm are beyond the scope of this dissertation. Each of these are complex issues in and of themselves and deserve special attention in future work. This exclusion is especially important as MoSS is designed in response to the lessons learned from Life Cycle Assessment in agriculture and farmer information management practices with respect to environmental sustainability. This work is primarily influenced by California Agriculture due to the scope of work in Chapter 4.

While many elements on a farm are specifically designed for animals — grazing pastures, modular pens, and mobile coops — animal-related elements are not specified in this version of MoSS. Some of the personas have livestock or aquatic elements, however, they were treated as `blackBox` elements or `structures`.

Similarly, humans are acknowledged, but not treated in detail. While humans are indeed part of an agricultural system; in this version of MoSS, humans are primarily considered as stakeholders of the models and data.

In this rest of this section, I will describe how each of the abstract elements (`system`, `components`, `resources`, `activities`, `data`) can be instantiated as domain-specific elements to model sustainable agricultural systems.

5.4.1 components

There are six types of domain-specific component elements: farm, field, structure, boundary, conveyance, and blackBox. An overview diagram of MoSS components in the domain of agriculture is shown in Figure 5.20.

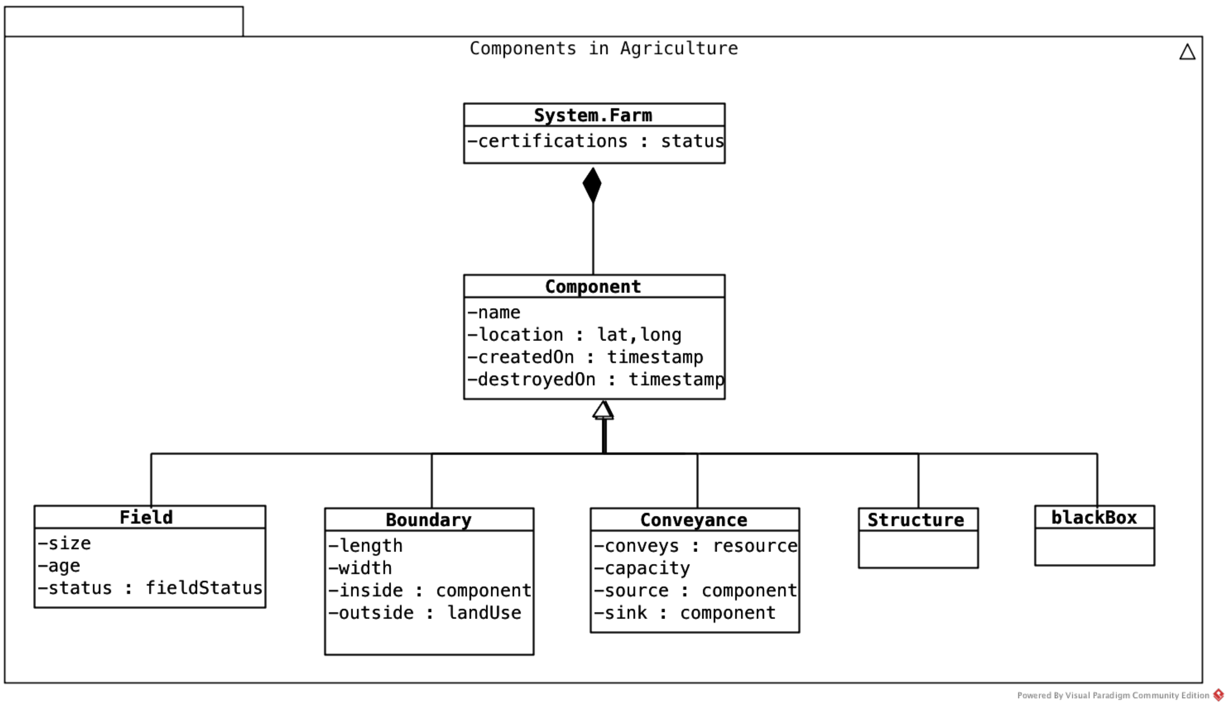


Figure 5.20: MoSS components in agriculture.

5.4.1.1 component.system.farm

The root system element in modeling sustainable agriculture is the farm. Subsystems within the farm are contained within this element (as demonstrated in Chapter 6).

5.4.1.2 `component.field`

In agriculture, land is typically dealt with in parcels [166]. A `farm` consists of one or more parcels of land that are further subdivided for different purposes on the farm. Each of these subdivisions of land, are `fields`.

Therefore, a `field` is a contiguous area of land used for agriculture. A `field` has five possible `[state]` values:

1. `empty`: a `field` begins as `empty`. It can then be designated for a particular use once it has undergone some initial activity such as having the land prepared for cultivation or
2. `cultivated`: a `field` that is `cultivated` is used to grow plants with the intent of harvesting them for sale.
3. `fallow`: a `field` that is `fallow` was previously `cultivated` but has been left to grow wild or planted with beneficial plants for least one season.
4. `protected`: a `field` that is `protected` is one on which the natural environment is actively preserved and improved. This includes the air, soil, water, flora, and fauna. However, this can also include the planting of native plants and the creation of native habitats for insects, birds, animals, and so on. The primary goal of the `field` must be to improve the natural environment. The farmer cannot commodify the crops and animals within this `field`: it is `protected`.
5. `water`: a `field` can also be used as a reservoir or pond. A `field` in a `water` state is an area of land within the `farm` that is filled with water for agricultural use.

Each `field` can be used for multiple concurrent agricultural activities, each of which is represented as a `layer`). A `cultivated` `field` therefore has one or more `layers` containing `crops`. These `crops` are planted on the land in certain patterns. Different crop types lend themselves to being planted in different `layouts`.

In MoSS, these patterns of cultivation are described as `layouts` of a `cropLayer` on a `cultivated field`, as shown in Figure 5.21.

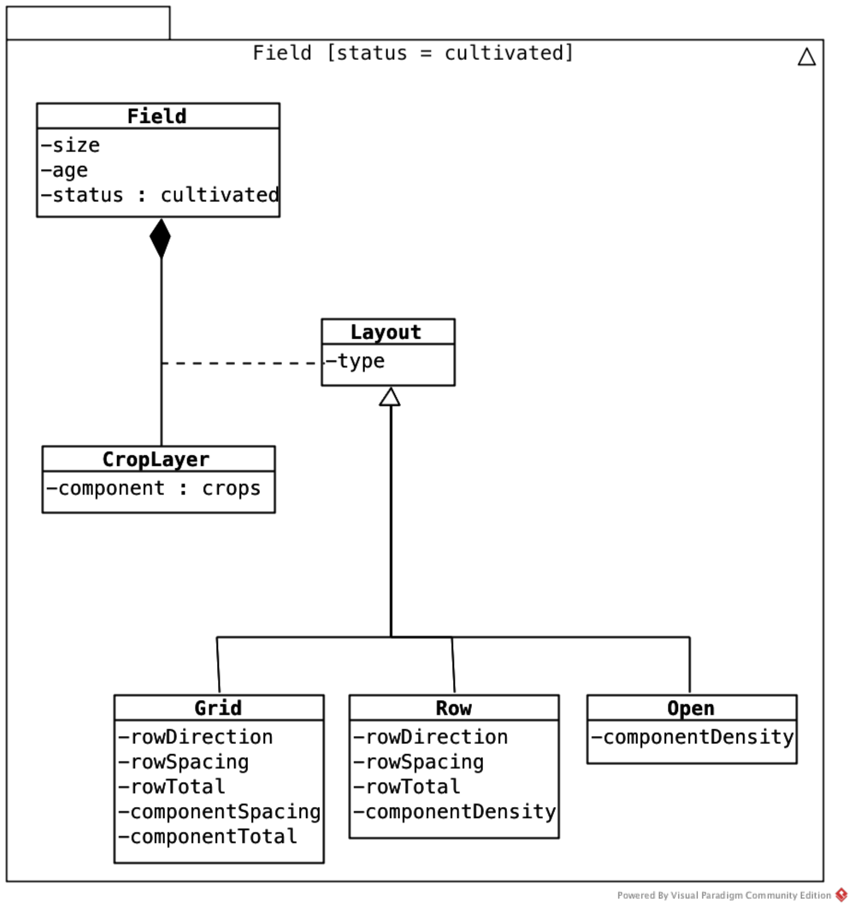


Figure 5.21: MoSS crop layer: Layout types available for a cultivated field.

`layouts` available for a `cultivated field` include:

- Rows: `row layouts` are typically used to plant vegetables and other row crops [67, 98, 216]. A `row layout` can have any of the following attributes specified: the distance between individual rows, the length of a row, the direction of a row, the number of rows in a field, either the density of seed in a row (e.g., 2 seeds per foot), or the distance between individual plants (e.g., 2 feet).

- Grids: `grid layouts` are typically used for trees, vine, and trellis crops [118, 127]. Many grid designs exist. Examples from orchard design include [127]:

    - Square or Rectangle: row spacing and tree spacing within each row is roughly the same.
    - Offset Square or Diamond: trees in adjacent rows are offset by half the space between trees within a row.
    - Hexagonal or Equilateral: All trees are equidistant from each other.

  Grid designs can be expressed as the relationship between row spacing and tree spacing. Therefore, the primary difference between a `row layout` and a `grid layout`, is that the distance between crops, and any offest between rows (and if so, by how much), must be specified. A `grid layout` can therefore be thought of as a more specific case of a `row layout`.

- Open: an `open layout` is one where seed was sprinkled on open land at a specific rate. Therefore, an `open layout` has a specific seed density.

5.4.1.3 `component.structure`

A `structure` can be used to represent the built environment. A structure is a contiguous spatial object created through human actions. `structures` can include the buildings, machines, and equipment used on the farm. Examples of `structures` include: farmhouses, sheds, silos, hullers, wells, greenhouses, barns, birdhouses and windmills.

5.4.1.4 `component.boundary`

A `boundary` can be attached to the perimeter of a `field`, `system`, or `structure`. A `boundary` separates two otherwise contiguous `components`.

For example, a `fence` can surround a `system`, separating it from neighboring land. A `path` can be used to separate `fields` within a `farm`. A row of trees, or `hedgerow`, can be used to separate a certified-organic farm from its conventional neighbor, or even the wilderness beyond.

The `[inside]` attribute refers to the `component` the boundary is attached to, however, one can also specify what the land use is `[outside]`. Types of land use are: agricultural, residential, commercial, industrial, and natural.

5.4.1.5 `component.conveyance`

A `conveyance` is a construction used to transmit a `resource` from one `component` to another. Examples include: a water pipe, an electricity line, a ditch.

A `conveyance` can also be modeled as a relationship between to `components` to denote that transfer of a resource between the associated components occurs via the conveyance.

5.4.1.6 `component.blackBox`

A `blackBox` is used to obfuscate the structural details of a `component`. It can be used to represent any physical aspect of a system, even the `system` itself. If a farmer wishes not to disclose proprietary details of a `system`, or does not feel it necessary to specify the details of a `component` for their modeling goals, a `blackBox` can be used. It allows for the modeling, for example, of `resources` going in and out of a `component`, without necessarily specifying how the `resources` are manipulated within the `component`.

5.4.2 `resources`

In agriculture, a "natural resource" typically refers to land or soil, water, air, and non-agricultural plants and animals [158, 110]. Each of these are also integral elements of a sustainable agricultural system. The role of such resources varies based on system type: what is being grown for sale, the sustainability of the agricultural practices, the types of inputs on the farm, and the various subsystems and activities on the farm.

For instance, in Certified Organic Agriculture, as defined by the United States National Organic Program [231], many materials that are applied to the land are supposed to be "natural". Compost is both a product of natural causes, but can also be created intentionally by a farmer as part of their sustainable agricultural practice.

Given this, the use of the category *natural* as a type of resource is not necessarily useful in modeling a sustainable system. A sustainable farm is a socio-environmental system, therefore there is no explicit category called *natural resource* in MoSS. Instead, the following `resource` subtypes are proposed as a means for modeling the resources that are used and produced in various sustainable agricultural `activities`. Land is essentially treated as a `component` in MoSS as it is simply a spatially bounded part of the larger `system:EARTH`.

An overview diagram of MoSS resources in the domain of agriculture is shown in Figure 5.22 (page 152).

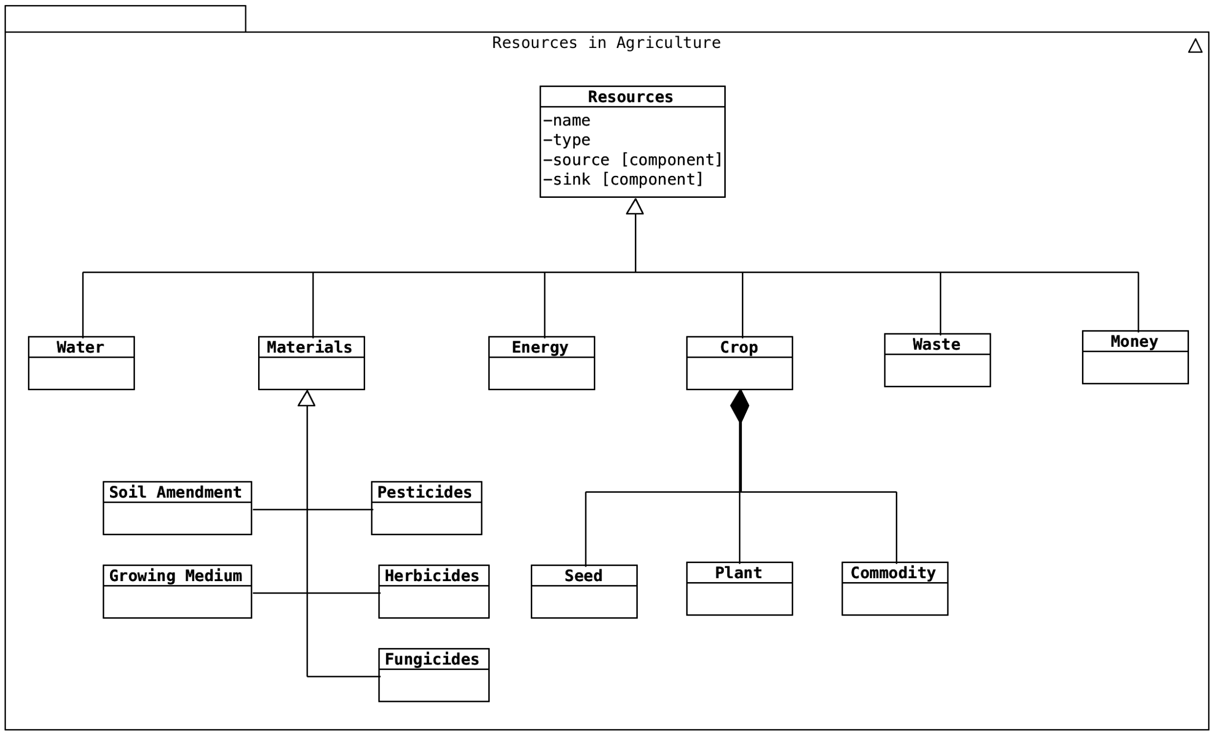


Figure 5.22: MoSS `resource` classification in agriculture.

5.4.2.1 `resource.material`

`materials` are `resources` used in various agricultural activities. These include fertilizers, pest and weed controls, and soil amendments.

5.4.2.2 `resource.water`

`water` includes any water that is used in agricultural activities: from irrigation, washing crops on harvest, to filled reservoirs.

5.4.2.3 `resource.energy`

`energy` includes any energy used in agricultural activities: whether produced on site, or bought from the local electricity grid.

5.4.2.4 `resource.crop`

`crops` are `resources` the are cultivated on `fields` in a `farm`. A `crop` resource can be decomposed into its constituent parts — seed, sapling, plant, fruit, commodity — for later use in crop-specific activities such as sowing and harvesting.

5.4.2.5 `resource.waste`

While some farm `waste` is an output that goes directly to sewage systems, landfills, or recycling facilities, there is, for example, organic waste that is produced on a farm that can be reused as a resource in other agricultural activities.

5.4.2.6 `resource.money`

`money` is a resource that is used to exchange goods and services provided by the farm, as well as to purchase goods and services required on the farm.

Resource Classification: The predefined types of `resources` proposed in this section should be considered a minimal set. Due to the blurred line between human systems and natural systems, it will be important to continue the specification of these model elements with domain experts. For example, where do biological controls fit in? Farmer Jane (study participant, Chapter 4), uses Decolatte snails as a biological control against brown snails (considered pests) [222]. In this case, both the Decolatte snail would technically be a resource input, but a classification conundrum exists — should it be modeled as an animal or a material resource due to its use in an activity? The goal of the farmer is not to necessarily raise the snails as part of the farm, but they did indeed introduce them into the farming system as a biological control.

Modeling food, energy, and water: The domain-specific elements of MoSS specified in this chapter are to enable the modeling of a farm. In this section, `water` and `energy` have been specified as `resources`. However, the process for modeling an irrigation system or an energy production system is also possible using the MoSS abstract elements previously described. I briefly demonstrate how an irrigation system can be modeled as part of an agricultural system in Scenario 6.3.3 in the next chapter.

5.4.3 `activities`

`activities` represent the things that are happening in, to, and because of the an agricultural system. Categories of `activities` will vary based on crops grown, animals raised, farming practices, knowledge sought, the environmental context, and the goals of the farmer, among other things. This means that the range of possible `farm.activities` is very broad. As opposed to listing a dictionary of `activities`, I describe a set of illustrative element-specific activities in the domain of sustainable agriculture. These demonstrate how `activities` can be specified depending on the actual system of interest.

The site at which an `activity` is said to occur can be as specific as an individual tree, or as broad as the farm-level. Regardless of scope, an `activity` must be associated with a `component`. The default `activity[site]`, is the `system`.

The relationships between `activities` and `components`, `resources`, and `data` is shown in Figure 5.23 (page 155). These `activities` can then be instantiated for the domain of agriculture depending on the system of interest.

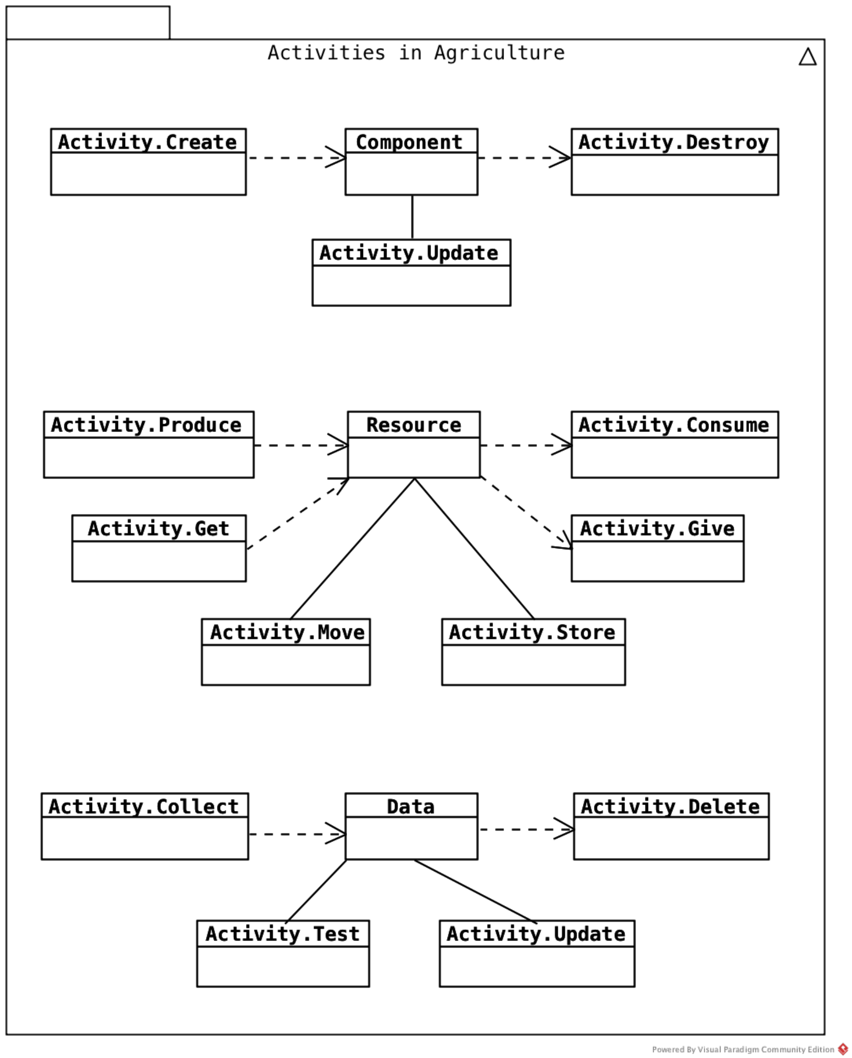


Figure 5.23: MoSS `activity` structures in agriculture.

5.4.3.1 `activities` — `component`

- `create`: a `component` is created in the real world.
- `destroy`: a `component` is destroyed in the real world.

- `update`: a `component` is changed in the real world.

5.4.3.2 `activities` — `resource`

- `get`: a `component` (including `resources` and `data`) enters the `system`. A special case of `get` is `buy`, where the `component` is exchanged for `resource.money` or some other element of perceived equivalent value. For example, a `resource.material` can be bought.

- `use`: a `resource` is used in an `activity`. Resource use can be further specified for the domain of agriculture. For example:

  - `resource.material -> field`: a material resource can be applied to a field.
  - `resource.water -> field/crop`: water can be used to irrigate a crop.
  - `(resource.crop -> field/cropLayer) | layout.row`: crops can be sown in a row layout on a field.

- `move`: a `resource` can be moved from one `component` to another. It does not undergo any transformation, only the point in space at which it is located changes.

- `store`: a `resource` is held for a fixed period of time in a `component`. It does not undergo any transformation, it is held in space as time elapses.

- `produce`: `resource` is produced as a result of an `activity`. Resource production can be further specified for the domain of agriculture. For example:

  - `field/tree.harvest -> crop.commodity`: Fruit can be harvested from a tree in a field.
  - `system.composter -> resource.material.compost`: Compost can be produced from a composting system such as an aerated pile.

- `give`: a `component` (including `resources` and `data`) exits the `system`. A special case of `give` is `sell`, where the `component` is exchanged for `resource.money` or some other element of perceived equivalent value. For example, a `resource.crop/commodity` can be sold.

5.4.3.3 `activities` — `data`

- `collect`: `data` about the `system` is recorded.
- `update`: `data` about the `system` is changed.
- `delete`: `data` about the `system` is deleted.
- `test`: a `sample` can be tested with respect to some condition. The output of this activity is `data` about the original component that was sampled.

5.4.4 `data`

As explored in Chapter 4 in detail, much data is collected regarding agricultural activities in sustainable agriculture. MoSS `data` elements are designed to contain four fundamental types of data that can be associated with any element in the MoSS model of a farm. These are overviewed in Figure 5.24 (page 158).

5.4.4.1 `data.observation`

Observational data is data that a human reports about their experience of the world. The data collection *instruments* are human sensors: sights, smells, sounds, textures. These can include opinions or reflections by the data collector. An `observation` is recorded in any natural language or captured via written text, recorded speech, or image creation.

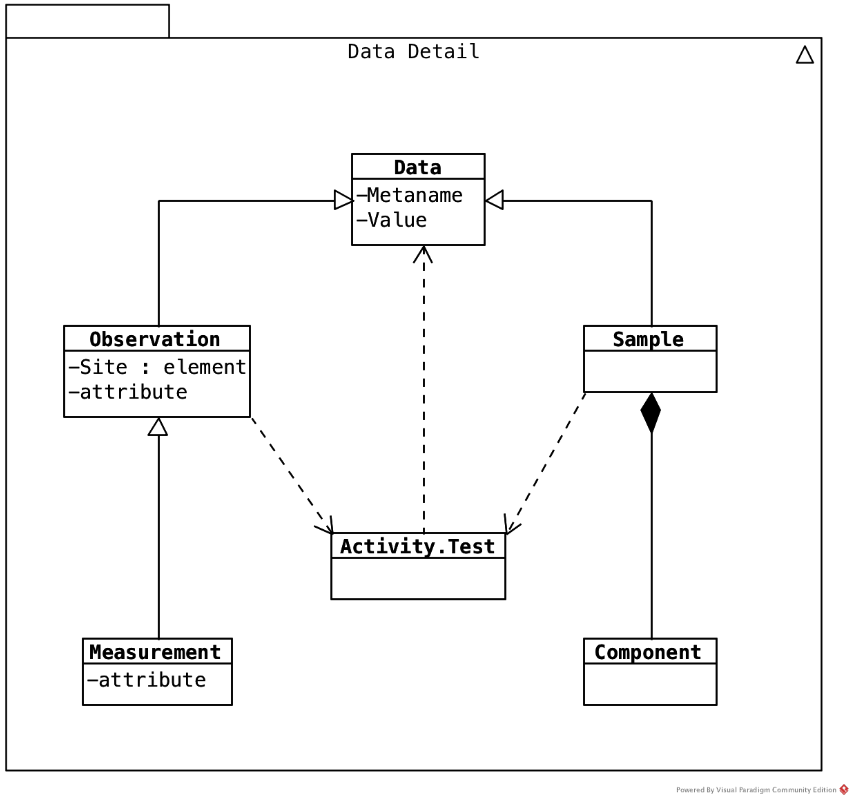


Figure 5.24: MoSS `data` types in agriculture.

5.4.4.2 `data.measurement`

A `measurement` is collected through the use of a non-human sensor, i.e., a tool. This includes data collected by digital and mechanical sensors such as a thermometer, calipers, accelerometers, and rain gauges. An `measurement` is recorded in any natural language or captured via written text, recorded speech, or image creation.

5.4.4.3 `data.sample`

A `sample` is representative piece that is extracted from the world. Things that can be sampled include: soil in a field, water used for irrigation, leaf tissue from a plant, or residue from a tree. `samples` cannot be physically included in a MoSS model, instead metadata about the sample must be modeled such as location of sampling, reason for sampling, amount, color. However, `samples` could also be in the form of photographs (picture of the residue on a tree) or recordings of sound (sound of a malfunctioning piece of equipment).

5.4.4.4 `data` — `activity.test`

A `test` can be conducted on any other `data` to further classify it, extract meaning, or calculate a result. For example, a soil sample can be tested to establish its chemical composition, water can be tested for pathogens, leaf tissue can be tested for nutritional value, or residue found on a tree could be tested to allow for identification. The results of a `test` can be recorded in any natural language or captured via written text, recorded speech, or image creation.

5.5 Example: The 1-acre Tomato Farm

In this section, I demonstrate how various MoSS elements can be used to create a simple *farm-to-gate* model. The goal of this example is to provide insight as to how elements can be used to represent farm data, capture various agriculture-related activities, and connect these to provide perspective on the farm as a system. This example is not intended to be an exhaustive demonstration of MoSS, but simply an illustration of the MoSS framework in action. This MoSS example is presented in five parts:

1. Planting tomatoes: Figure 5.25, page 160.
2. Crop irrigation: Figure 5.26, page 161.
3. Observing and responding to fungus: Figure 5.27, page 162.
4. Harvesting and selling tomatoes: Figure 5.28, page 163.

5. Full farm-to-gate model. Figure 5.29, page 164

Part One: Consider first, a 1-acre tomato farm as modeled using MoSS in Figure 5.25. It consists of a 1-acre field that has been planted with San Marzano tomatoes.

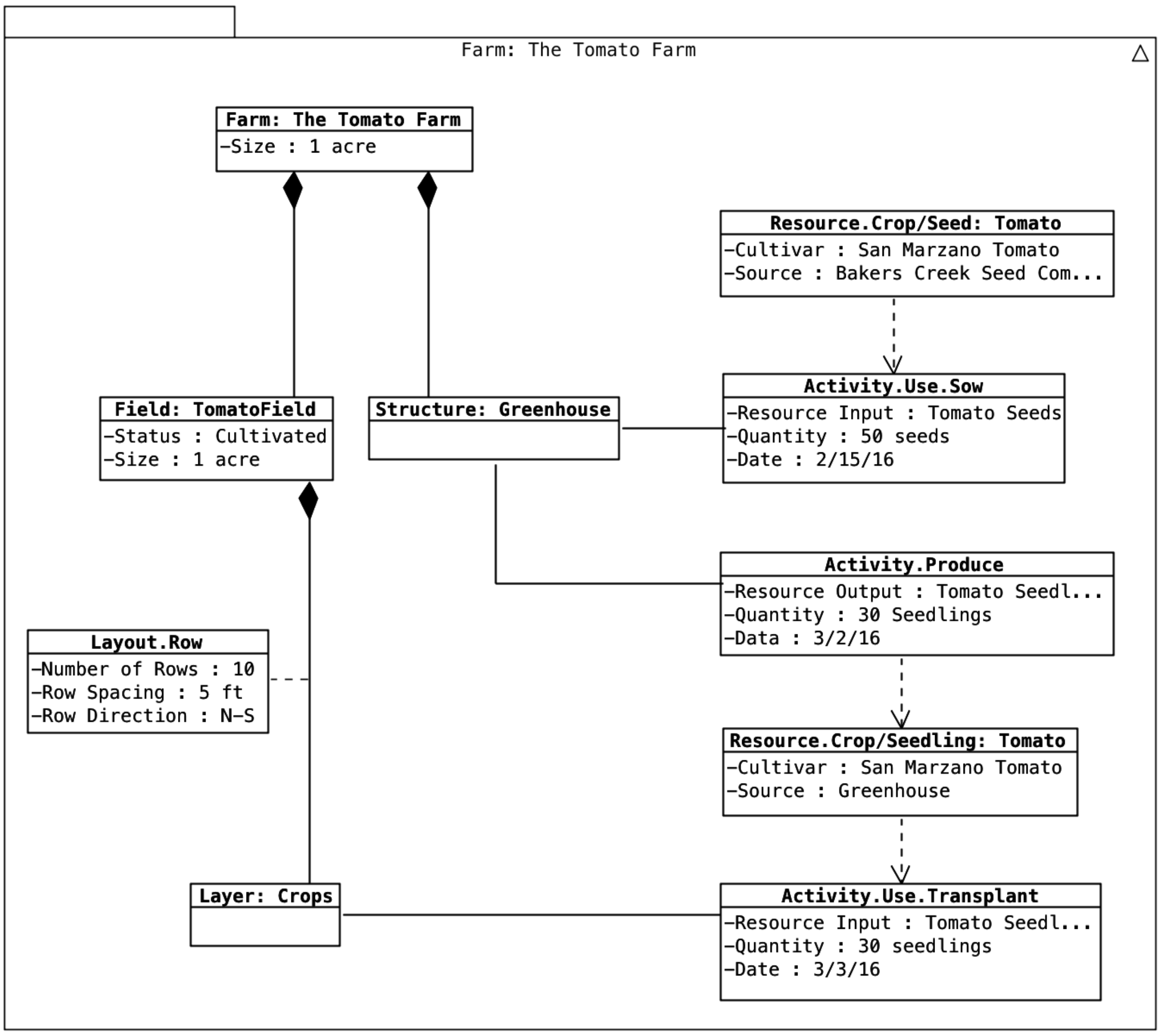


Figure 5.25: The 1-acre Tomato Farm, partial MoSS model.

The tomatoes are represented as a `layer` on the `field:TOMATOFIELD` that has been planted in `rows`. However, tomatoes are not typically planted directly in a field. Seeds are first sown in a `structure:GREENHOUSE`, these grow to become seedlings, that are eventually transplanted to the field. A series of `activities` Figure 5.25, of which the inputs and outputs are the different stages of the plant, are used to represent this maturation process.

Part Two: The field of tomatoes is irrigated with water from the north well. The quality of the well water has been tested water and no issues were found. The irrigation activity and associated elements are modeled in Figure 5.26.

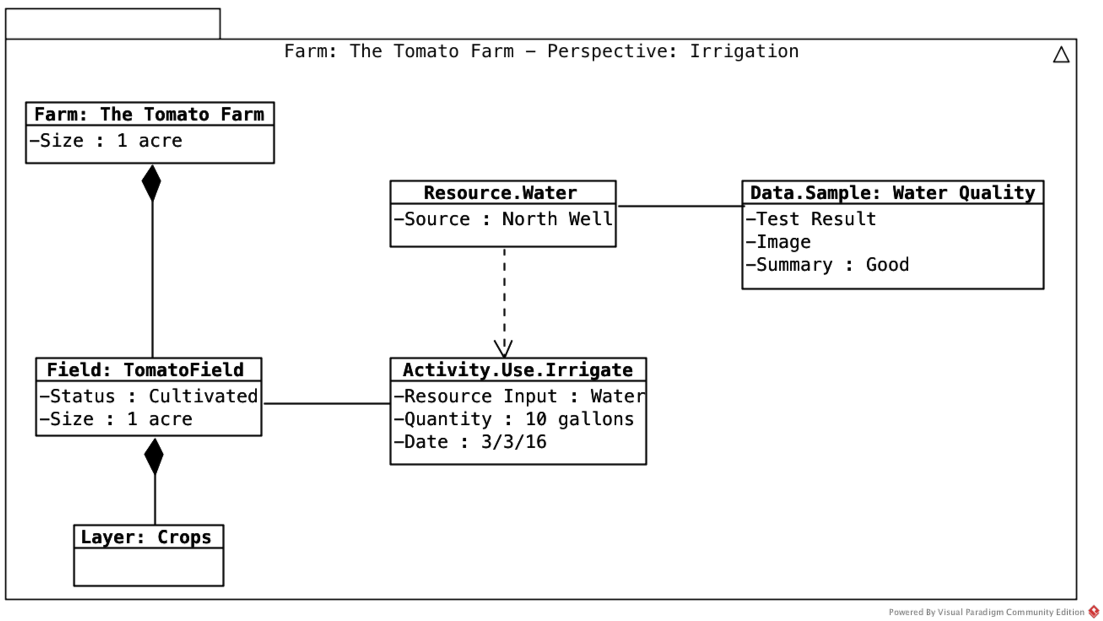


Figure 5.26: The Tomato Farm: Partial MoSS model, irrigation.

`Activity.Use.Irrigate` is associated with the entire crop layer, as water is delivered to the whole field and water consumption is not measured per crop. However, if water was delivered and measured at the individual plant level, then the activity would need to be associated with a plant object.

Part Three: A fungus is found on several tomatoes in the field. A fungicidal spray was applied to the tomato field to address issue. Both the observation of the fungus and the activity conducted in response are modeled in Figure 5.27 (page 162).

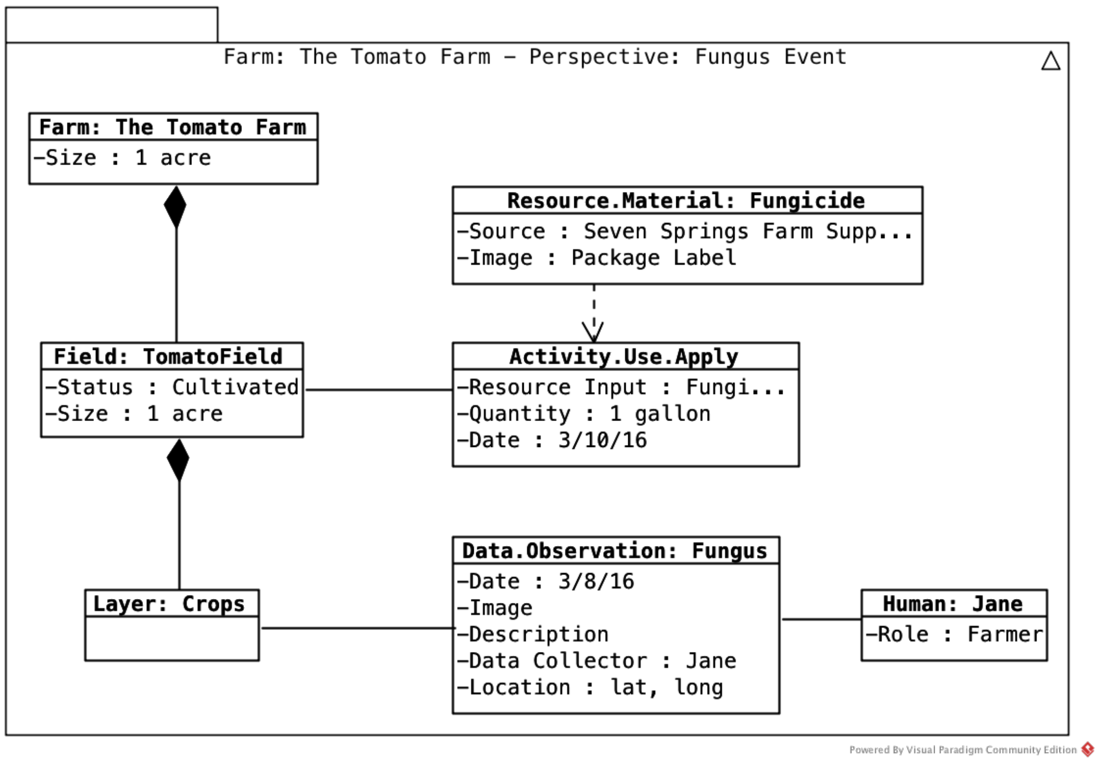


Figure 5.27: The Tomato Farm: Partial MoSS model, dealing with fungus.

As the fungus is observed on several tomatoes, it is associated with `layer:CROPS`. However, the fungicide, in this instance, is once again applied to the field. There is also an element representing the farmer who collected the data: `human:JANE`. While there are currently no explicit MoSS elements to represent humans, I use this `human` element to represent farm workers in this example only.

Part Four: A farm worker spent the day picking the tomatoes. These tomatoes are sold. These harvest and sale activities are modeled in Figure 5.28.

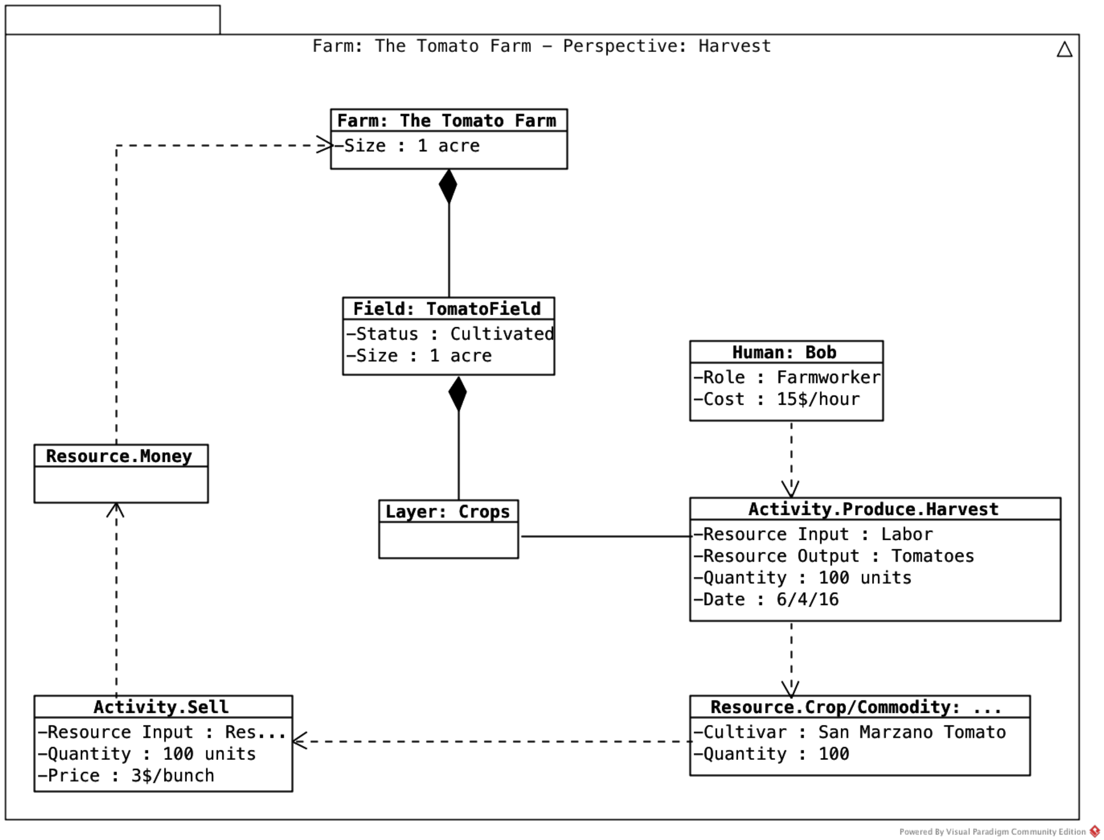


Figure 5.28: The Tomato Farm: Partial MoSS model, selling tomatoes.

This set of activities closes the production loop as the act of selling the tomatoes results in input of the the `Resource.Money` to the farming system.

Once again, Bob, the farmworker is represented using the `human` element to demonstrate the full farm-to-gate model. Here, I also represent the cost of labor, and consider that as the resource input to `Activity.Produce.Harvest`. In future iterations of MoSS, I will need to revisit the representation of humans as a part of an agricultural system. In the rest of this dissertation, I treat humans as actors, and do not represent their involvement with the farm in MoSS models outside of this example.

Part Five: Finally, we can connect each of the partial models of Parts one to five, to create farm-to-gate MoSS model of The Tomato Farm. Figure 5.29 contains each of the tomato production activities and components to create a whole system model of a season of tomatoes at the 1-acre tomato farm.

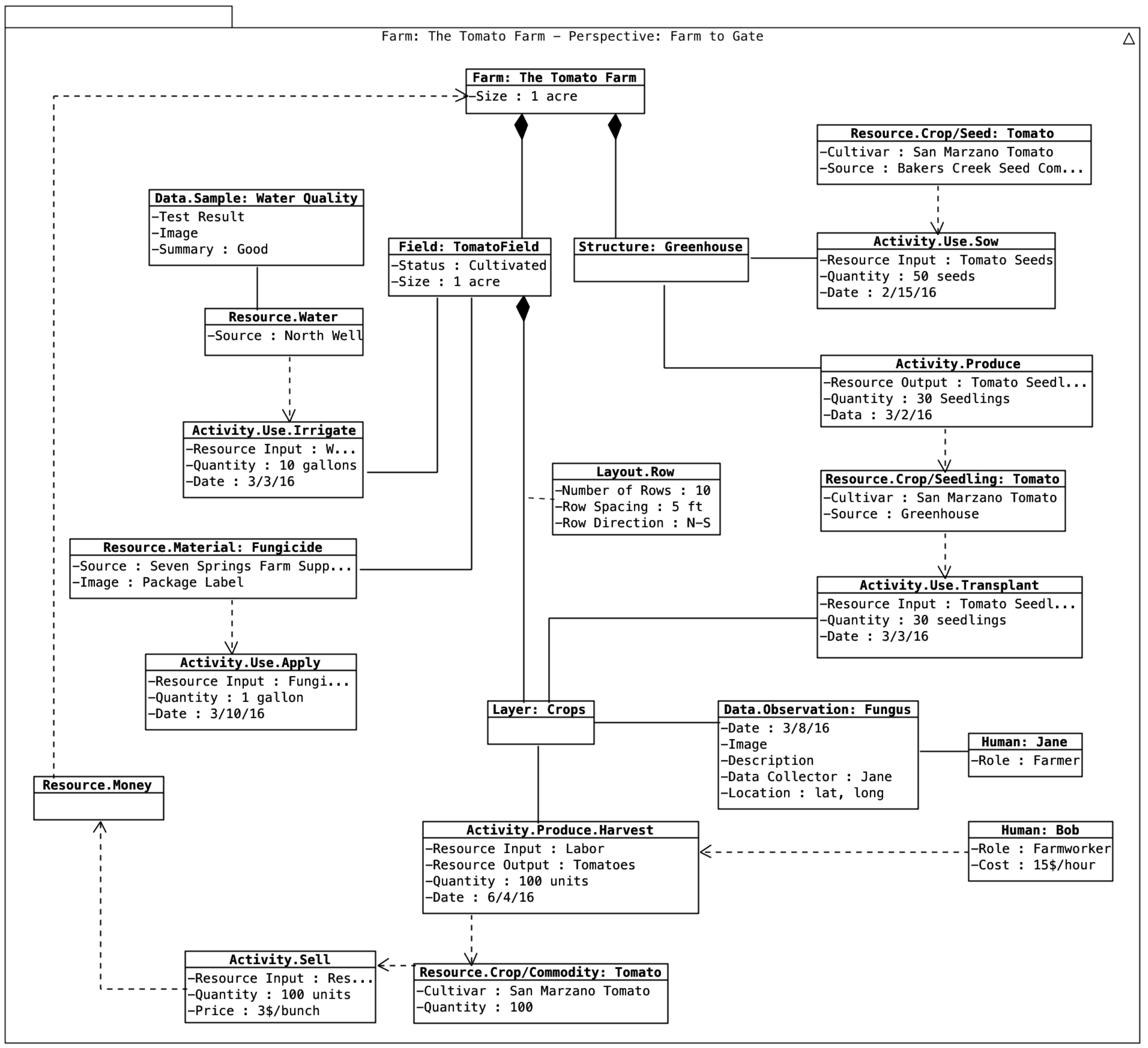


Figure 5.29: The Tomato Farm: Full farm to gate MoSS model.

5.6 MoSS `perspectives`

A `system` model can be subset using a `perspective` to allow for selective viewing of the model to meet a specific modeling goal. Creating a `perspective` allows for grouping, prioritizing, filtering, and checking, of `components`, `activities`, and `data`. A `perspective` shows/hides model elements based on set of conditions such that only the elements of interest are presented.

5.6.1 Perspective Rules

Perspective Rules are written in pseudocode based on the MoSS grammar described in Section 5.2.2, Python-style loops, conditions, and boolean operators [176]. In MoSS, we can use `perspective` rules to declare what what the conditions are for a particular perspective, or to check a model with respect to a particular set of conditions.

5.6.2 Perspective Types

I define five types of perspectives that offer some encapsulated logic.

1. `inventory`: Show only `system` elements of a specific element type.
2. `scope`: Show only `system` elements that are children, parts of, or associated with, a specific element(s).
3. `context`: Show all `system` elements a specific element(s) is a part of or is a child of.
4. `obfuscate`: Hide associated elements that are children, parts of, or associated with, a specific element(s) in a `blackBox` component.

5. `filter`: Show only `system` elements that match a `perspective` rule.

6. `assessment`: Show all `system` elements required to check a model with respect to a set of conditions representing some external question.

5.6.3 Perspective Examples: Space, Time, and Assessment

In the following three examples, I demonstrate how perspective rules can be used, in conjunction with `perspective` types to create perspectives for a MoSS model. These examples reference the 1-acre Tomato Farm, first presented in Section 5.5.

5.6.3.1 `perspective.space`

This `perspective` shows only `components`: the goal is to provide the modeler with insight into the physical structure of the system. This `perspective` represents the land, structures, objects — that is, things in the real world. It can be visually represented through a map and corresponding box and arrow diagrams.

A `space perspective` provides a structural snapshot of the `system`. The following spatial perspective results in the MoSS model shown in Figure 5.30:

Spatial Perspective

```
farm: TOMATO FARM - perspective: SPACE:
  filter (components)
```

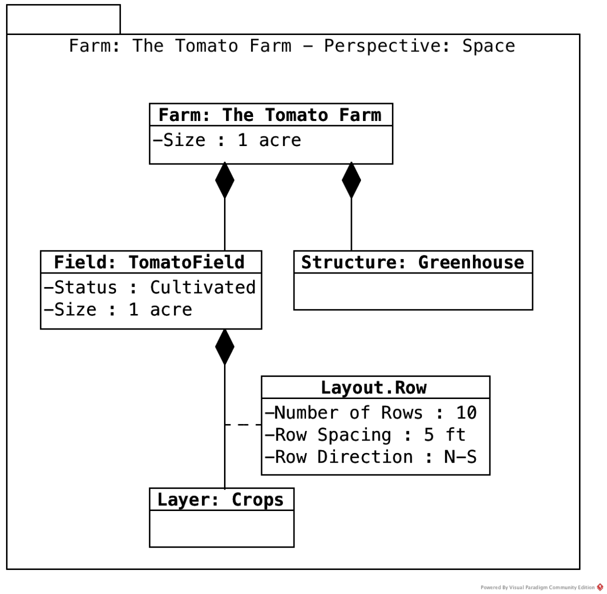


Figure 5.30: The Tomato Farm: Components only.

5.6.3.2 `perspective.time`

This `perspective` shows only `activities`: the goal is to provide the modeler with insight into how system behavior and the chronology of `activities`. This `perspective` represents the processing, creation, movement- the changes experienced by things in the real world. It can be visually represented through a calendar and corresponding box and arrow diagrams.

A `time perspective` provides a glimpse into both resource flows and the activity history of a `system`. Figure 5.31 displays a MoSS Model for the following temporal perspective:

Temporal Perspective

```
farm: TOMATO FARM - perspective: TIME:
  filter (activities)
```

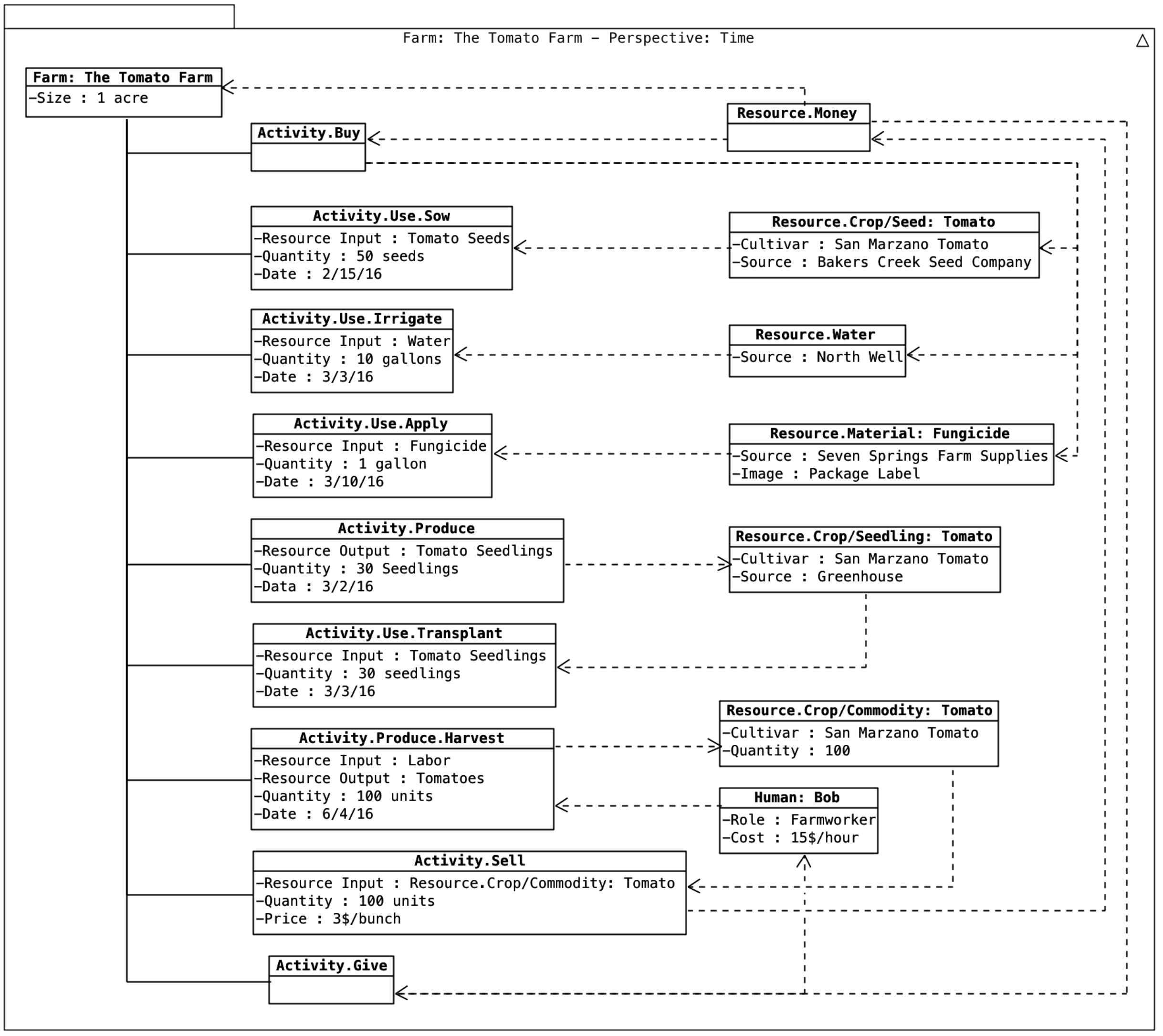


Figure 5.31: The Tomato Farm: Activities (and resources) only.

5.6.3.3 `perspective.assessment`

In software and systems modeling, there is a tradition of creating model checkers to exhaustively and automatically check' to see if the farm model meets the environmental assessment specification [61].

We can use `perspectives` to create rules to check a MoSS model agains a particular set of conditions. These conditions can represent, for example, the requirement for a farm to be certified organic. An example of an organic assessment perspective is available in Chapter 6, Section 6.4.2.

An assessment `perspective` can also be used to calculate, for example, the water footprint of a farm by adding the values of all water inputs to a farm, or:

Assessment Perspective

```
farm: TOMATO FARM - perspective.assessment: WATER FOOTPRINT:
  for (R in (resource.water -> farm)):
    farm [waterFootprint] += R [quantity]
```

5.7 MoSS Modeling Heuristics

Goal Driven Modeling

1. Analysis goals should dictate perspective creation. The purpose of creating a model is to gain perspective on a system of interest. We model because there is something about a system that we'd like to learn more about. We model because we're trying to gain perspective on a system. It follows, that before one creates a MoSS model of any system, a modeling goal must be defined. This will determine what information we need to know about the system, what data structures we need to create, what information we don't have about the system, and what data collection activities we may need to engage in.

2. Only model what is needed. When creating a model, it is of the utmost importance to have a distinct scope; however, boundaries are not sufficient as- not every model within the boundary need be modeled. Keeping the modeling goal in mind, one only needs to model the components pertinent to the question(s) one is trying to answer.

Abstraction and Modularity

3. Model parts of speech. Continuing with the analogy of question asking, consider the creation of a model like the writing of a sentence. Nouns can be modeled as MoSS `components`, verbs as MoSS activities, and adjectives as MoSS data. Consider the sentence: *five large peaches are harvested from a field.* This can be modeled as:

```
field -> resource.crop/commodity:PEACH [quantity = 5])
                     - data.measurement:quality [size = LARGE]}
```

4. Use layers to create hierarchies of elements within components. Systems can often be decomposed into their constituent components. These components may sometimes be arranged in particular ways, but can also be nested within the parent component. As opposed to laying out components in a flat model, consider the use of hierarchies and other MoSS relationships, to nest, cluster, and group components within layers.

5. Use blocks to create activity templates. Groups of activities are often subject to particular orders of operation. Blocks should be used to represent common sequences of activities. These can be thought of as templates, as blocks can be reused each time a set of activities is performed within a system.

6. Use layers, blocks, and blackBoxes for encapsulation. Often, we do not need to specify the details of a particular system. Layer, blocks, and blackBoxes can be used to obfuscate details of a particular structure or set of processes that do not need to be exposed.

7. Extend elements when greater specificity is needed. The MoSS domain specific elements, as they are currently specified, do not cover all possible types of activities, components, data, and resources in the world. That is to say, if a desired element does not exist, refer to the abstract model to identify a root object that the desired element belongs to and specify accordingly.

Separation of Concerns

8. Separate spatial and temporal dimensions. At the core of the MoSS abstract model is the distinction between two fundamental elements: component and activity. This has been designed to respect the essential properties of structural and behavioral elements in a system. While activities occur within physically bounded spaces, these spaces are subject to the ravages of time. By separating the two, we allow for both static and dynamic analyses of systems, that is, it allows for both viewing the snapshot of a system and examining trends over time.

9. Separate data from components, activities, and resources. Reusability is at the heart of MoSS. To be able to create models in which elements can be reused to meet different modeling goals, we need to have elements that represent the essential properties of a system. Separating data from these elements allows for both the reuse of such elements in other perspectives, as well as enables the manipulation of the data without affecting structural or temporal perspectives of the system.

Avoiding pitfalls

10. Beware of over-specification. Systems are inherently complex. Just because we have information about a system does not mean that we must model it. When creating a MoSS model, there is a danger that too many elements are modeled- this over-specification may distract from the true intent of the model.

11. Avoid isolated elements. When an element is not connected to any other element within a MoSS model, there is likely an issue. Systems are inherently interconnected. This mean that for every property of a system that is represented to meet a modeling goal, there must be some relationship with at least one more other element(s).

12. Know the way in and out, even in a circle. Even when representing a fully integrated, self-sufficient, cradle-to-cradle, system, it is important to recognize that this system exists within some greater context. Regardless of how circular a MoSS model may appear, at some point elements must enter and exiting the system. Even if there is not an explicit entry or exit point, knowing the primary source and final sink of the system as a whole is vital to contextualizing the MoSS model.

Chapter 6

Evaluating MoSS in Agriculture

It is now necessary to demonstrate the efficacy and expressiveness of MoSS. In this chapter, I describe a scenario-based evaluation of the MoSS framework in the context of sustainable agriculture. Three *Farm Personas* are used to evaluate MoSS. That is, given each Persona, a set of scenarios is imagined to require the creation, manipulation, and use of MoSS models to reflect on various perspectives of a sustainable agricultural system. The scenarios have been designed to represent a range of sustainable agricultural systems and practices. They pose a series of modeling challenges that allow for the stress-testing of MoSS. Further, these scenarios demonstrate how farmers can structure farm data to gain insights as to the performance of their agricultural systems, and to conduct a variety of system assessments.

Chapter Overview: Section 6.1 describes the method in which both a set of Farm Personas and associated scenarios were designed. In this section, I formally introduce *Farm Personas* as a device for both design and evaluation of the MoSS framework. While they were previously used in the MoSS design process, as briefly touched on in Section 5.1 of Chapter 5, the Farm Personas explicitly presented in this chapter only. The next three Sections, 6.2, 6.3, and 6.4, contain a Farm Persona description along with the scenarios themselves. Finally, in Section 6.5, I evaluate MoSS given the scenarios presented, discuss threats to the validity of the evaluation, and pose some open questions that need to be address in future work.

6.1 Methodology

The evaluation of MoSS relies on the use of two tools: personas and scenarios. In this section, I describe the design and use of personas that represent farms, briefly noting their prior use in the design of MoSS, while focusing on their role in the MoSS evaluation process. I also describe how and why scenarios were designed, both in relation to the personas, and the goals of this evaluation.

6.1.1 Farm Personas for Design and Evaluation

Personas are detailed constructions of fictitious yet archetypal users of a software system that allow for human-centered design [175, 51]. There is growing interest in using personas to engage in design that considers other forms of system interaction. For example, collaboration personas have been used for the design and evaluation of tools for use by groups of humans [138]. Non-human animal personas [77] were proposed in recognition that the human stakeholder should not entirely dictate prototype development: a cow is a user of a robotic milking device, and the cow's needs, welfare, and experience in mind, should dictate the design of the tool.

Farmers are integral actors in agricultural systems. Often, in addition to being the farm's owner/operator, a farmer is also: a manager of staff, the primary decision maker regarding on-farm activities, a stakeholder of farm data, and a farm data collector. While future work involves the design of a modeling tool to allow the farmer to interact with MoSS, the scope of this dissertation is to design a mechanism for modeling sustainable agricultural systems. I therefore consider farmers as primary actors in a *System Persona*.

I define a *System Persona* as a detailed construction of a fictitious yet archetypal system. As the focus of this dissertation is on the holistic representation of the characteristics of small- to medium-scale sustainable agricultural systems, I created a set of *Farm Personas*, where each persona represents a hypothetical small- to medium-scale sustainable farm in California.

Considering farms through the lens of a persona allows us to gain insight into the system itself. The Farm Personas needed to support two activities:

1. Design of a modeling framework to represent small- to medium scale farms.
2. Evaluation of the modeling framework with respect to the modeling requirements of sustainable agriculture.

In this section, I describe how five Farm Personas were designed to support each of these activities.

Step One: Creating the base Farm Persona. First, the coverage and inclusion criteria, detailed in Section 4.1, Chapter 4 (used to determine the range of farms needed for the qualitative study), were combined to determine the range of Farm Personas needed. Each of the Farm Personas must:

1. Represent sustainability-oriented agricultural systems.
2. Fit the description of a small- to medium-scale family farm.
3. Represent a farm producing food for sale to the public.

Additionally, at least one Farm Persona needed to:

1. Represent at each of the following commodity types: field crops, tree crops, vine crops, and vegetable crops. Livestock were treated as actors, and not explicitly considered as commodities in this work.
2. Be in one of two California Farming regions: Central Valley or the Central Coast and Southern region. The third region, North Coast and Mountain, was not considered as there was no farm data covered for this region in Chapter 4.

Table 6.1 overviews the five base Farm Personas that were created based on these criteria.

Table 6.1: Farm Personas.

Persona Name	County*	Size**	Commodities	Age
1. Blackbird Gardens	Monterey	10	Vegetables, strawberries	2-5
2. Luna Orchard	Fresno	40	Citrus fruit and products	10
3. Sundance Ranch	San Diego	90	Specialty grains, livestock***	25
4. Wild Valley Vineyard	Santa Barbara	15	Wine	5
5. Maribel Farms	Yolo	150	Vegetables, fruits and nuts, livestock***, grains	50

* County in California, U.S

** Size in Acres

*** Livestock treated as actors, not explicitly considered.

Seven actors, representing hypothetical farmers, are also associated with these personas. Table 6.2 lists the actors associated with each Farm Persona, and indicates which personas were used in the design and/or evaluation of the MoSS framework.

Table 6.2: Farm Personas, further detail. Indication of persona use in design and/or evaluation activities.

Persona Name	Associated Actors	MoSS Design	MoSS Evaluation
1. Blackbird Gardens	Harvey Jones	✓	✓
	Suraj Jones		
2. Luna Orchard	Melika Vincent	✓	✓
3. Sundance Ranch	Jose Rivera	✓	✗
	Cassie Lee		
4. Wild Valley Vineyard	Chihiro Nakano	✓	✗
5. Maribel Farms	Jacob Smith	✓	✓

Step Two: Augmenting the Farm Personas for use in the Design of MoSS. The goal of this activity was to flesh out the Farm Personas with enough details so as to be used as part of the Persona Driven Design of MoSS, as described in Section 5.1 of Chapter 5.

The Farm Personas needed to be grounded in both the academic literature regarding formal modeling in sustainable agriculture (as described in Chapter 3), as well as the findings regarding sustainable farms in reality (as described in Chapter 4). Overview tables were created to map out the key characteristics of the 16 farms from Chapter 4, Farms Atwood to Pullman (A-P). These led to the creation of design parameters for the MoSS Farm Personas. These parameters reflect greater nuance (in comparison with the coverage and inclusion criteria) regarding the characteristics of the farms.

Once the base Farm Personas were created, they were augmented through the addition of characteristics from the 16 farms resulting in artificial yet data-rich composite farms. Two primary characteristics were used to augment the Farm Personas to engage in the design work that resulted in the MoSS framework: complexity and dynamism. This process is briefly described next.

Complexity: Farm layout diagrams were created for each of the participating farms to understand varying farm structures. A sample of these is shown in Figure 6.1.

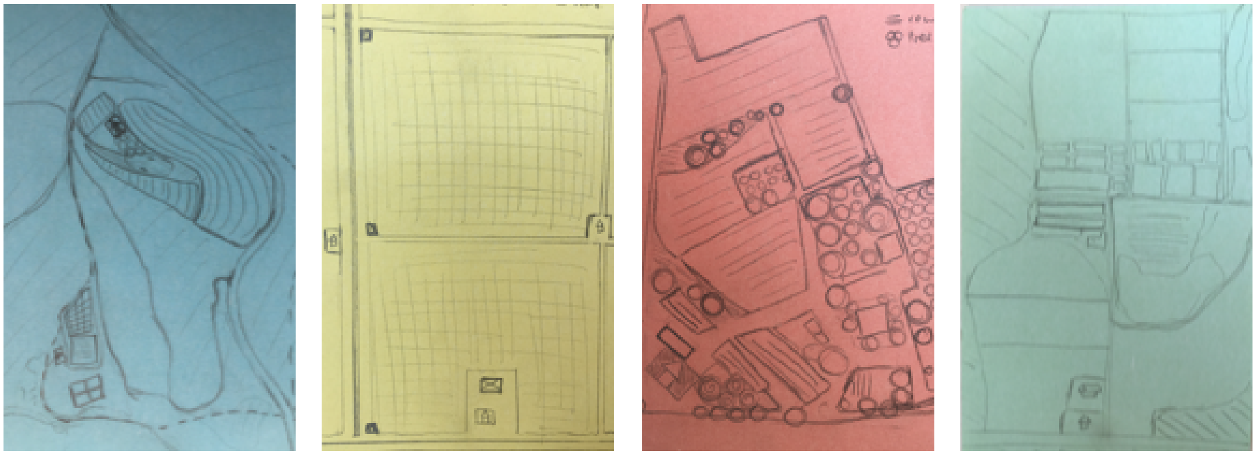


Figure 6.1: Redrawn layout diagrams of four real farms: Atwood Organic Vineyard, Iyer Orchards, Campbell Farms, and Huang Integrated Farms.

The layout of farms is typically determined by geography, cultivation systems, livestock, environmentally sensitive regions, and farmer design. Table 6.3 summarizes the resulting Farm Persona layouts specifications.

Table 6.3: Farm Personas: Complexity.

Persona Name	Structure, Layout, and Complexity
1. Blackbird Gardens	Geographically oriented layout with environmentally sensitive areas.
2. Luna Orchard	Rectangular, grid based layout.
3. Sundance Ranch	Dynamic layout, alternating pasture and field crops, moving irrigation lines.
4. Wild Valley Vineyard	Geographically oriented layout.
5. Maribel Farms	Mixed layout as determined by a complex crop mixture.

Dynamism: The vertical and horizontal integration of each of the 16 farms (that participated in the qualitative study) was explored: Figure 6.2 shows the distribution of farm based on commodity complexity versus process complexity.

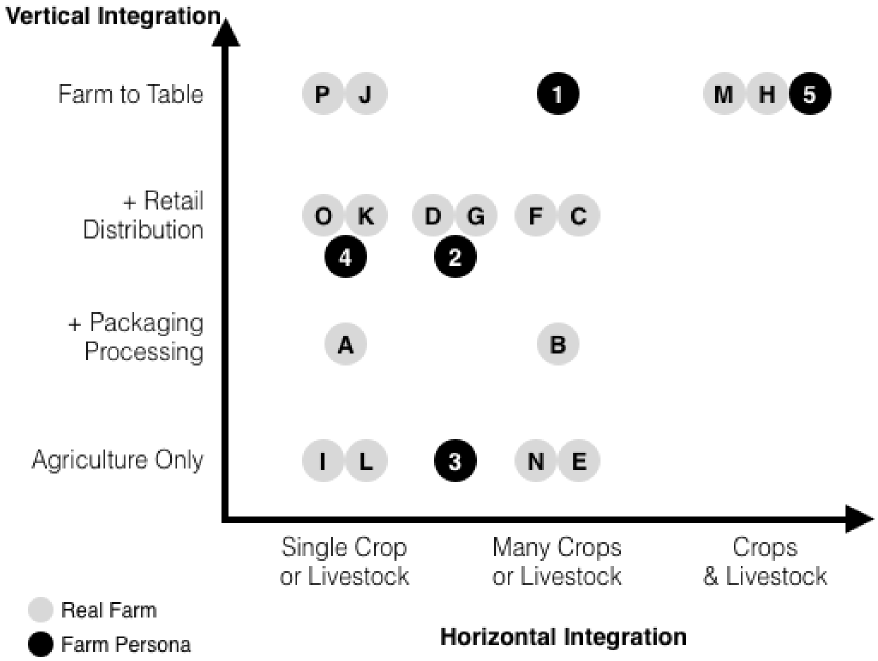


Figure 6.2: Distribution of the 16 participating farms (A-P) based on increasing horizontal integration versus increasing vertical integration. The five personas are also mapped onto the diagram, numbered 1-5.

For example, Iyer Orchards (Point I) was a single cropping system where trees were grown and whole nuts harvested. The farm was only responsible for the crops up to the farm gate. After that, an external wholesale buyer is responsible for transporting the crops off the farm property. This system is therefore concerned with *Agriculture Only*.

On the other hand, Huang Integrated Farms, (Point H), was a fully integrated system consisting of many types of crops and multiple species of livestock. They grew, packaged, and distributed their commodities, going so far as working directly with consumers to produce grow and home-deliver, for example, fish. Marsden Organic Orchards (Point M) similarly takes responsibility of many crops and livestock from the beginning of the life cycle on the farm, through to delivery to, for example, a consumers home or a restaurant. These farms are both highly integrated both horizontally and vertically.

Each of the five Farm Personas were spread across integration distribution to demonstrate varied levels of crop and process diversity, temporal complexity, scope of activity, and overall dynamism. The Farm Personas are numbered on Figure 6.2 (page 179). Table 6.4 summarizes the resulting horizontal and vertical integration represented in each Farm Persona.

Table 6.4: Farm Personas: Dynamism.

Persona Name	Horizontal and Vertical Integration
1. Blackbird Gardens	Many crops are produced at the farm. Crops are grown and delivered to consumers.
2. Luna Orchard	Many varieties of a single crop (citrus) are grown, however the farmer is only responsible for agriculture, packaging, processing, and distribution.
3. Sundance Ranch	A single type of livestock and several varieties of field crops are grown, however they are rotated with no integration between the system. The farmers only focus on the cultivation of crops and raising of the animals.
4. Wild Valley Vineyard	Many varieties of a single crop (grapes) are grown to produce several types of wine. These are then sold to consumers via a third party distributer.
5. Maribel Farms	An integrated farming system with many crops and livestock covering the full life cycle of food from farm to table.

Step Three: Augmenting the Farm Personas for use in the Evaluation of MoSS. Once the design work was complete and the MoSS framework articulated (presented in Chapter 5), a subset of three Farm Personas were selected for further augmentation and subsequent use in the scenario-based evaluation (presented in this chapter). The personas essentially required greater detail with respect to environmental assessment and information management practices. This process, was closely tied to the design of the scenarios to ensure that the Farm Personas were adequately specified. This augmentation process is described next.

Information Management: Chapter 4 contains a classification of types of farm data collected for use in a range of on-farm activities, from environmental assessment to day-to-day farm management. Each of the Farm Personas were specified with farm management requirements to utilize various types of farm data. This is summarized in Table 6.5.

Table 6.5: Farm Personas: Farm management.

Persona Name	Farm Management Goal(s)
1. Blackbird Gardens	Manage crop rotations and enable coordination and collaboration among farm workers
2. Luna Orchard	Investigate crop health issues
5. Maribel Farms	Maintain farm records for farm management and organic certification and

Environmental Assessment: Among the 16 farms described in Chapter 4, those that did conduct some form of environmental assessment did so to obtain a certification, to meet a regulation, or to meet some internal assessment goal. No formal environmental assessments, such as Life Cycle Assessments, were conducted at these farms. Given this, MoSS needed to first, at minimum support certification or regulation oriented assessments, but not necessarily a full Life Cycle Assessment. Each of the Farm Personas were specified with environmental assessment goals as summarized in Table 6.6.

Table 6.6: Farm Personas: Environmental assessment goals.

Persona Name	Environmental Assessment Goal(s)
1. Blackbird Gardens	Assess efficacy of environmental stewardship practices
	Maintain farm records for evenetual organic certification
2. Luna Orchard	Track water use on the farm for water-use optimization
5. Maribel Farms	Asses farm records for compliance with organic certification requirements

These three Farm Personas — Blackbird Gardens, Luna Orchard, and Maribel Farms — were finally used to enact a series of scenarios to evaluate the MOSS framework. The next section describes the design of the scenarios for each of these Farm Personas.

6.1.2 Scenario-Based Evaluation

A scenario is a hypothetical set of activities to be enacted by actors interacting with a system of interest in the real world [24]. Scenarios have been used in software engineering and HCI research both as a means to explore potential designs of a system [37], as well system evaluation [101]. For example, Sutcliffe [207] describes how scenarios may be used in requirements engineering, in particular, to check abstract models through use of scenarios as a substitute for formal verification.

Scenarios are often implemented when the problem domain is "squishy" [202], i.e., the problem boundaries are not distinct, the interactions are complex, and the problem does not lend itself well to linear design work or structured evaluations. It follows that there is evidence of the use of scenarios for design and evaluation in the environmental assessment and sustainable agriculture communities. In LCA research, scenarios have even been used to represent hypothetical agricultural systems [19] to explore, for example, the environmental impacts of various pig production systems.

The University of California Cooperative Extension (UCCE) has been conducting "Sample Cost of Production Studies" for various farm commodities since 1928 [221]. While the early reports are written in the style of a handbook, later reports in the mid-2000s begin to list study assumptions in the style of a scenario.

For example, the 2009 cost production report for organic leaf lettuce in the central coast region of California, begins with a description of hypothetical farm with specific production activities; labor, interest and equipment; and how cash and capital are spent and obtained [216]. It is these characteristics of a fictitious farm that provide context for the various cost estimates that are subsequently listed. This structure is powerful as it allows the reader insight to the rationale for listed costs, contextualizes the calculations, and provides a human-readable example that a reader may work through. These cost production studies also proved an invaluable model for tailoring the software-style scenarios for sustainable agriculture.

Scenarios design process: There are eight scenarios described in this chapter that were used to evaluate MoSS. The primary basis for scenario creation were the findings of the qualitative study involving 16 sustainability-oriented farms in California, described in depth in Chapter 4. To ensure scenario accuracy, interview data were also checked against relevant literature prior to being incorporated into a scenario.

To avoid overspecialization and simply designing for those 16 farms (or for that matter the five Farm Personas), I created a set of scenarios, applicable to farms throughout a spectrum of sustainable agriculture. These scenarios were then enacted using three Farm Personas.

Much agricultural and environmental assessment literature utilize case studies and scenarios as a means to demonstrate problem areas, exemplify good practices, to provide guidance to the agricultural community, and to create public awareness. These materials provided supplements to the data and findings presented in Chapters 3 and 4 and were valuable (though not ideal) substitutes for domain-expert guidance.

Major resources for scenario-content guidance were:

- Case Studies in Agriculture: For example, the NRC publication "Toward Sustainable Agricultural Systems in the 21st Century" contains 11 illustrative case studies to investigate the state of "alternative" agriculture [158].

- Agricultural Assessment Scenarios: For example, [110] contains five scenarios assessing various aspects of the food system, including agricultural systems, and their effects.

- Agriculture Education Materials: For example, the University of California Cooperative Extension [221] provides lecture materials, instructional videos, expert guidelines, and public seminars geared toward both the agricultural community and the general public.

- Sustainable Agriculture Conferences: At both EcoFarm [64], and Future Harvest [80], I attended lectures on information management, the policy context of sustainable agriculture, and environmental assessment workshops run by various certifying and regulatory agencies.

- Agriculture in the Media: I found much supplementary information about farm-life, challenges, and complexities in the plethora of media focused on agriculture: from podcasts, farmer-oriented magazines, to farm social media accounts.

Overview of Persona-Scenarios sets: The structure of each persona-scenario set, as articulated for the scenario-based evaluation, is outlined in Table 6.7 (page 185).

The first scenario for each Farm Persona is designed to explore structural complexity of farms. The subsequent scenarios describe sustainable agricultural practices and environmental assessments that involve modeling farm components, activities, resources, and data. An overview table containing all persona-scenario sets is available in 6.8 (page 185).

Table 6.7: Persona-scenario set structure.

Each Persona contains:	
Overview:	Introduces the agricultural system, relevant geographical and environmental context, any major defining features or challenges, and associated human actors.
Management	Describes the management structure of the farm including farmer roles and responsibilities, and any additional labor.
Sales:	Describes the primary income streams and rationale.
Goals:	Describes high-level farm goals corresponding to each of the scenarios.
Each Persona has a set of scenarios. Each Scenario contains:	
Prelude:	Any relevant background information such as the policy or environmental context is described here.
Scenario Goal:	A one sentence goal is that directs the walkthrough.
Walkthrough:	This contains the main body of the scenario, presenting informal and MoSS, as well as supplementary information to inform the modeling process.

Table 6.8: Overview of scenarios.

Persona	**Blackbird Gardens**	**Luna Orchard**	**Maribel Farms**
Actors	Harvey, Suraj	Melika	Jacob
Scenarios	1. The Structure of a Farm pg. 188 2. Crop Rotations pg. 190 3. Environmental Stewardship pg. 196	1. Multilayer Layouts pg. 202 2. Diagnosing a Tree pg. 205 3. Tracking Water pg. 211	1. A System of Systems pg. 217 2. Organic Certification pg. 219

A gentle reminder: All farms presented in the remainder of this chapter are *Farm Personas*. That is, fictitious design artifacts intended to reflect the complexity, dynamism, and spectrum of sustainable agriculture in California. All names, places, systems, and people are fictitious, and any likeness to any individual, entity, or farm, is unintentional.

6.2 Blackbird Gardens

Farm Overview: Blackbird Gardens is a 10 acre fruit and vegetable farm nestled on the banks of Salinas river, east of the Monterey Bay. It sits at the top end of the Salinas Valley, an area colloquially known as the *Salad Bowl of the World* [199]. In 2011, 73% of US lettuce was grown in the Salinas Valley [83]. Primary commodities at Blackbird Gardens are leafy greens including lettuce, several varieties of brassicas, and seasonal vegetables such as summer tomatoes and fall pumpkins.

Figure 6.3: Blackbird Gardens: Geographical context.

The land on which Blackbird Gardens is located was once a conventional artichoke field, but since Harvey and Suraj Jones bought the land in 2010, they have been transitioning the land to support a more sustainable agricultural system. The farm is bordered by conventional vegetable farms of varying scales, with the exception of a river on the southern border.

Farm Management: While Harvey and Suraj own the land on which Blackbird Gardens is located, the ownership structure of the farming operation is a partnership with four additional farmers. All six partners live on the farm across four residences. Each of the partners have different farming expertise, backgrounds, and responsibilities. For example, Suraj leads the salad greens production and as well as the overall management of the protected areas on the property. Harvey's primary responsibilities involve utilizing the day-to-day farm data, collected and recorded by each of the farmers, to manage the farm business. Suraj and each of the four additional farmers are responsible for the cultivation of different crops and directly lead field work. The goal of this ownership structure is to allow for a diverse team to come together, lending their unique perspectives to the practice of sustainable agriculture.

Farm Sales: The crop commodities from the farm are sold through the following avenues:

- On-Farm Stand: There is a a weekly farm stand open on the property to allow for consumers to visit the farm and purchase produce.
- Community Supported Agriculture (CSA): Produce is available for pickup at the On-Farm Stand, as well as delivered to select drop off locations weekly. There are currently 50 CSA share members.
- Farm to Table Restaurants: Produce is delivered directly to 10 restaurants in the greater central coast area. Each chef receives larger customized CSA shares (for example, they can place requests for additional specialty crops).

Farm Goals: The farmers at Blackbird Gardens are dedicated to sustainably producing seasonal crops as both local environment and consumer demands shift. The farm mandate is to preserve and improve the natural environment, create and restore habitats for native plants, animals, and insects, and promote local sustainable agriculture, while maintaining an economically viable and socially responsible farming operation.

Current farm goals are:

- To improve coordination and collaboration among the six farmers.
- To provide nesting sites for the endangered Least Bell's Vireo.

- Maintain 5 years of records so as to obtain organic certification for each of the fruits and vegetables grown on the farm.
- Focus on quality, stability, and sustainability.

6.2.1 Scenario One: The Structure of a Farm

Scenario Goal: Describe the structure of Blackbird Gardens.

Walkthrough: Crops are cultivated on six fields on the farm, with each field named (by the farmers): Alpha through Epsilon. The overall farm layout is shown in Figure 6.4.

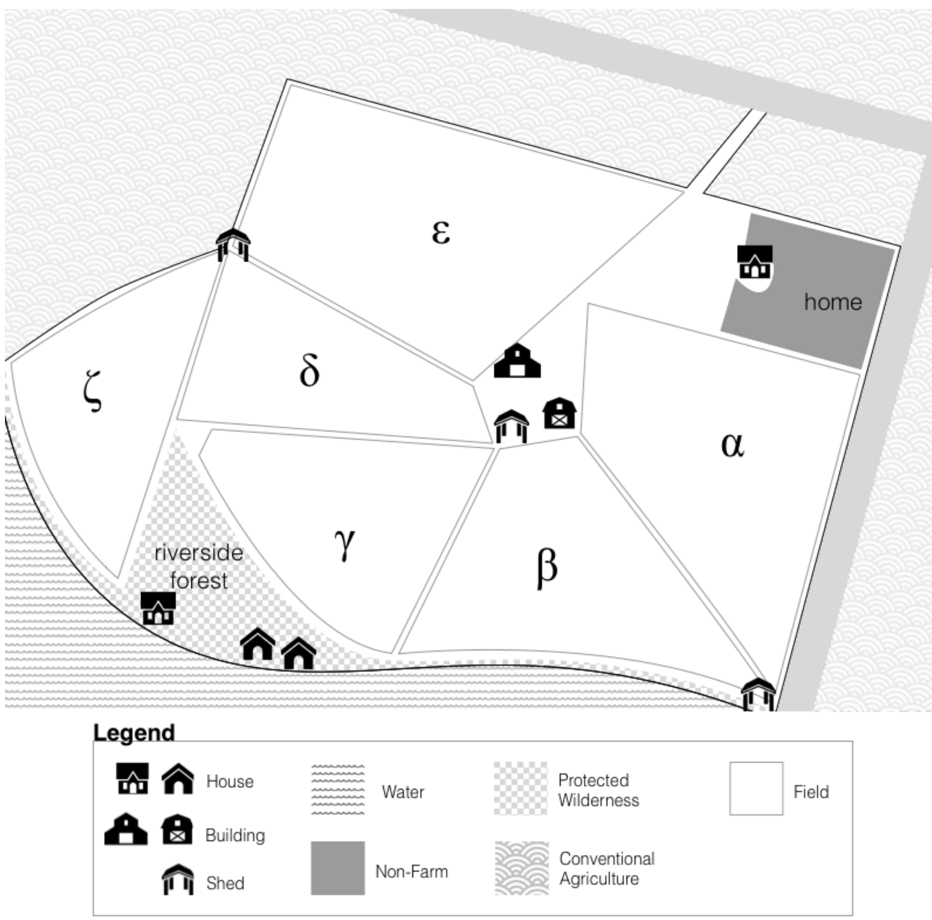


Figure 6.4: Blackbird Gardens: Farm layout map.

A two-acre wilderness area is located on the southern border of the farm, where the farmers have planted and preserved native trees and plants. This area, by the riverside, also contains the Blackbird Garden's Bed and Breakfast building and two residential buildings in which four of the farmers live. Harvey and Suraj's home is located at the northeastern corner of the farm, on a small garden field on which they grow fruits and vegetables for personal consumption. The Jones' home also serves as the main office for the farm. At the center of the land, is a cluster of buildings, including a processing shed where fruits and vegetables are washed and packed for transport, a barn containing equipment and machinery, a shed containing a small break room and amenities for all farm employees. There are two more break-sheds located on either end of the farm.

The farm layout can also be expressed using MoSS `components` as shown in Figure 6.5 below:

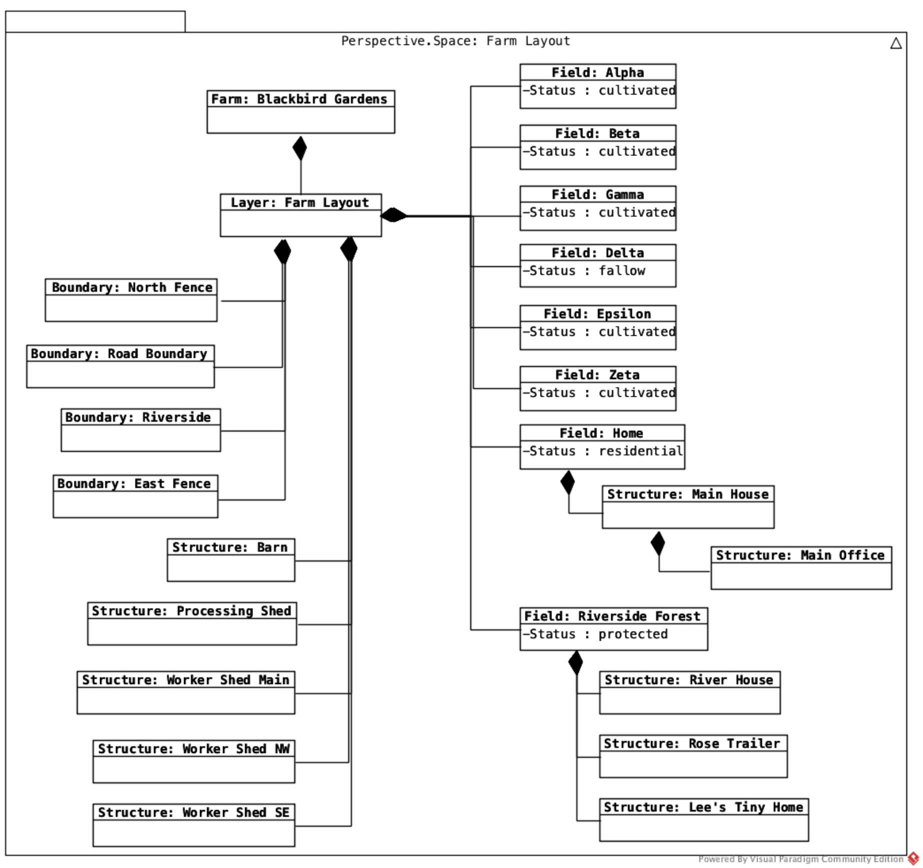


Figure 6.5: Blackbird Gardens: Farm layout, MoSS model.

This MoSS model describes the `perspective:` FARM LAYOUT. There are many other details about the farm that have not been expressed in these diagrams. There are various fruiting trees growing at different locations on the farm (that are indeed harvested for sale, albeit opportunistically), bird and bat boxes, beehives, a compost pile, etc. However, the goal for this diagram is to describe the major components on the farm and their relative location within the hierarchy of the `farm:` BLACKBIRD GARDENS, (the root Component) — that is, to provide perspective on the farm layout.

6.2.2 Scenario Two: Crop Rotations

Prelude: Blackbird Gardens has a 50 member Community Supported Agriculture (CSA) program. In addition, they provide select restaurants with produce in the form of larger, partially customizable CSA shares (e.g., special request additions or varied crop ratios). The farmers must plant crops across the farm that result in a diverse CSA share containing balanced harvests: some starchy tubers, plenty of fibrous vegetables, a bounty of pantry staples, and a sampling of new foods to expand the eater's horizon [170].

The farmers must also keep in mind seasonality of crops with respect to the local climate and consumer demands throughout the year to devise planting schedules that result in appropriate crop yields that fulfill all regular customers' (CSA members and restaurants) requirements at the very least.

Crop rotation is a core practice in sustainable agriculture [158]. A crop rotation is defined as a "system of cultivation where different crops are planted in consecutive growing seasons to maintain soil fertility" [238]. However, it is both useful for creating a planting schedule that allows for a diversity of crops to be grown in a small area, as well as sequencing plants in a manner that cares for soil health and environmental quality [103].

Successful crop rotations involve significant planning and forethought, good record keeping and data collection practices, and sensitivity to the complex interactions and relationships among various crops, soil health, water requirements, and labor [43]. The practice of crop rotation results in a highly dynamic schedule of crop-related activities at Blackbird Gardens.

Farmers therefore create a "crop plan" to manage crop rotations [42]. The record keeping involved in managing crop rotations is a crucial to the sustainability of a vegetable farm. Many farmers, including Harvey, use a combination of worksheets (as shown in Figure 6.6 below) and associated spreadsheets to create crop plans, but these are both time and effort intensive.

YEAR:

DATE	FIELD	CROP/VARIETY	SEED CO.	HOLE #	# OF BEDS	# OF ROWS	# OF FEET	DAYS / GERMINATE	DAYS / MATURE	FIRST HARVEST	LAST HARVEST	TOTAL YIELD	NOTES

Figure 6.6: Crop planning worksheet [42].

Scenario Goal: Manage long-term crop rotations at Blackbird Gardens.

Walkthrough: First, consider the annotated farm layout in Figure 6.7 (page 192). This reflects what is currently planted in each field.

A static MoSS model representing the current crop layout is shown in Figure 6.8(page 192). However, this represents a snapshot of the farm's overall crop rotation plan as it shows what is planted where during a specific time: i.e., what is planted in each of the fields during the last week of Spring 2017.

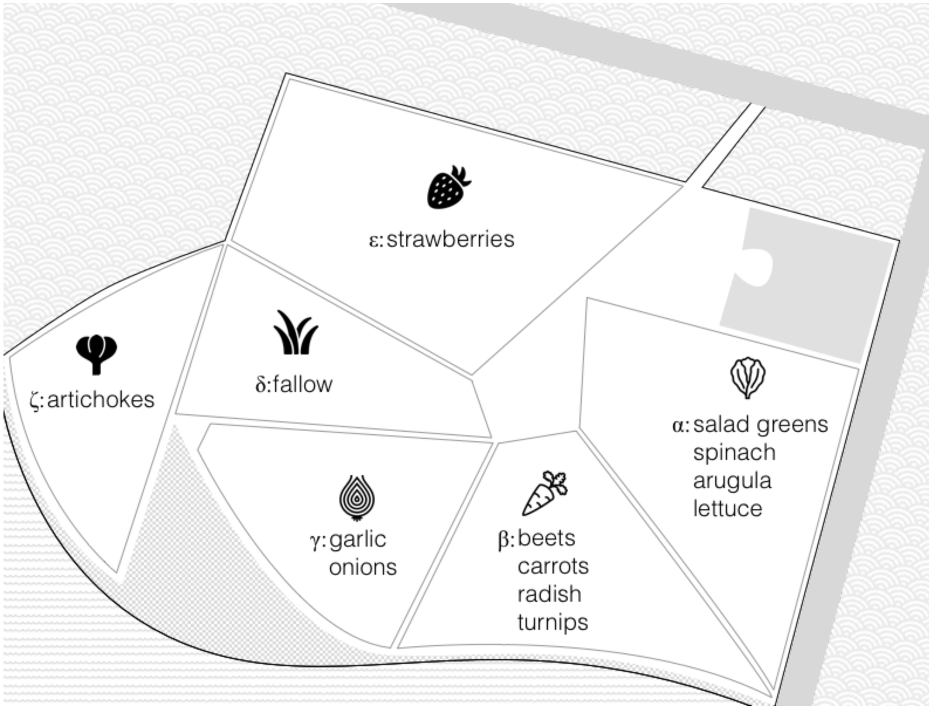


Figure 6.7: Blackbird Gardens: Snapshot crop layout.

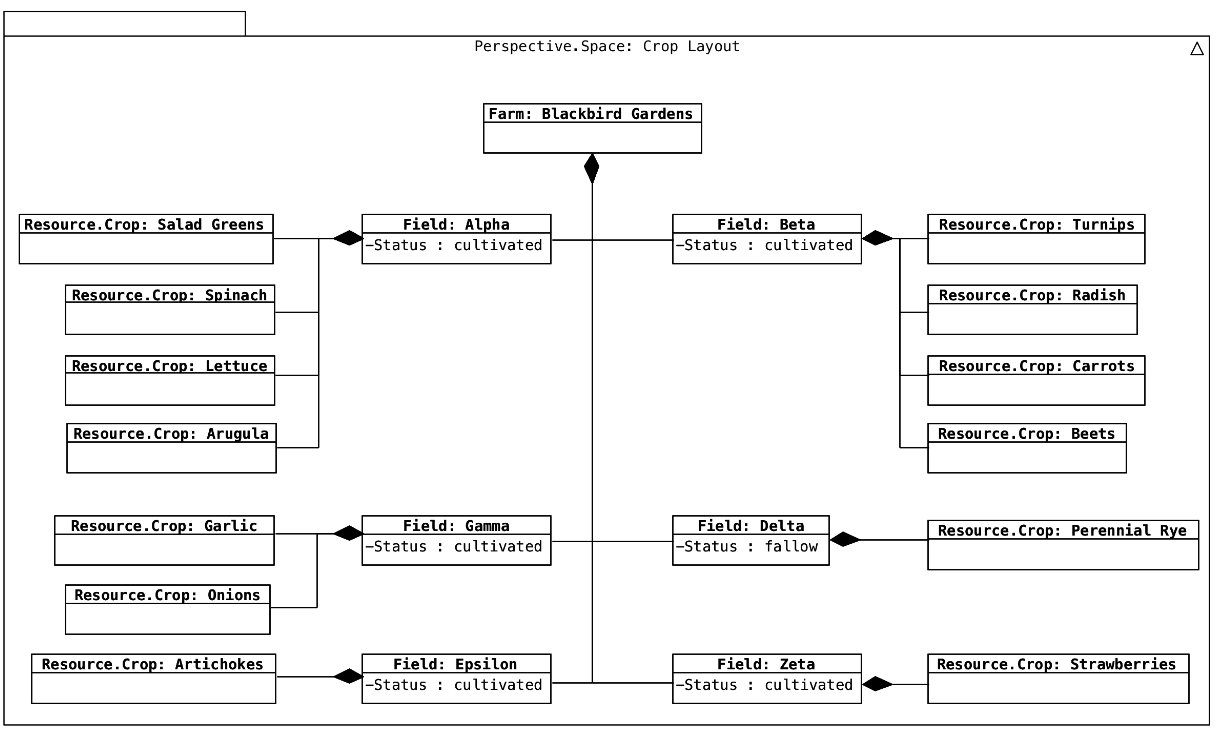


Figure 6.8: Blackbird Gardens: Snapshot crop layout, MoSS model.

In actuality, a multi-year crop rotation plan (here on *Crop Plan*) is set up for each field (and, subsequently, the farm as a whole). It dictates the order in which a field will be planted with specific crops to allow for, for example, the soil to recover after a particularly nutrient-intense crop. The Crop Plan also includes fallow seasons, which are seasons during which the crops planted (or allowed to grow wild) are not harvested for sale. In this example, Perennial Rye is planted during the fallow period, mowed, and tilled into the soil to allow for the introduction of beneficial organic matter into the land [43].

Figure 6.9 (page 193) is a calendar of crop rotations for multiple years at Blackbird Gardens.

Crop Rotation	Spring		Summer		Fall		Winter
Year 1						perennial rye planted	perennial rye establishes
Year 2		perennial rye mowed	perennial rye mowed and irrigated bi-monthly	5-10 tons per acre compost applied	rye spaded onion/garlic beds formed pre-irrigated	onions/garlic planted	onions/garlic weeded as needed
Year 3	onions/garlic weeded as needed		onions/garlic harvested	summer cover crops planted	winter cover crops planted		
Year 4	winter cover tilled in	carrots, beets, turnips planted	crops planted, harvested	crops planted, harvested	crops harvested	winter cover crops planted	
Year 5	winter cover tilled in	potatoes planted		potatoes harvested	ground prepared for cover crops	winter cover crops planted	
Year 6	winter cover tilled in	greens planted, harvested	crops planted, harvested	crops planted, harvested	crops harvested	ground prepared winter cover crops planted	

Figure 6.9: Blackbird Gardens: Multi-year crop rotation plan.

One can infer what stage of the Crop Plan a specific field is at by correlating the crop layout snapshot in Figure 6.7, and with the scheduled plantings in Figure 6.9. For example, Field Beta is currently planted with four crops: carrots, turnips, beets, and radishes. It is in Year 4 of its crop rotation.

However, as the goal is to manage long term crop rotations, a mechanism to capture the capture changes as crops are planted and harvested, changes in seasons, and crop rotation refinements, is required.

In MoSS, a crop rotation can be represented as a predetermined sequence of activities, colloquially called a "round of plantings" [43], intended to produce the desired yield of crops to meet production and environmental goals. A `block` can be used to represent each round of growing a particular crop.

The MoSS model in Figure 6.10 (page 195) consists of three simplified rounds of plantings in Field Beta, spanning across approximately five seasons: from late Spring of Year 4 through the end of Summer in Year 5.

This `perspective` would allow the farmers to collaborate on decision making, reflect on efficacy of the crop plan, and to refine the rotations to improve soil health and meet their customer demands for diverse CSA shares.

Managing long-term crop rotations can also allow Harvey and the other farmers to answer questions about Blackbird Gardens such as:

- How much of each type of crop, whether seed, seedling, root stock, or whole plant, needs to be ordered? Further, can a budget be created for the year given anticipated water, material resource, and equipment costs?
- Does the the proposed crop rotation adequately take into account soil health. For example, does a nitrogen-fixing crop follow a nitrogen-intense plant, or is there an adequate fallow period planned after a particularly nutrient-intense plant?
- Is an adequate variety of crops being produced during each season to meet customer needs? Further, are reliable crops paired with risky crops in a financially responsible manner?

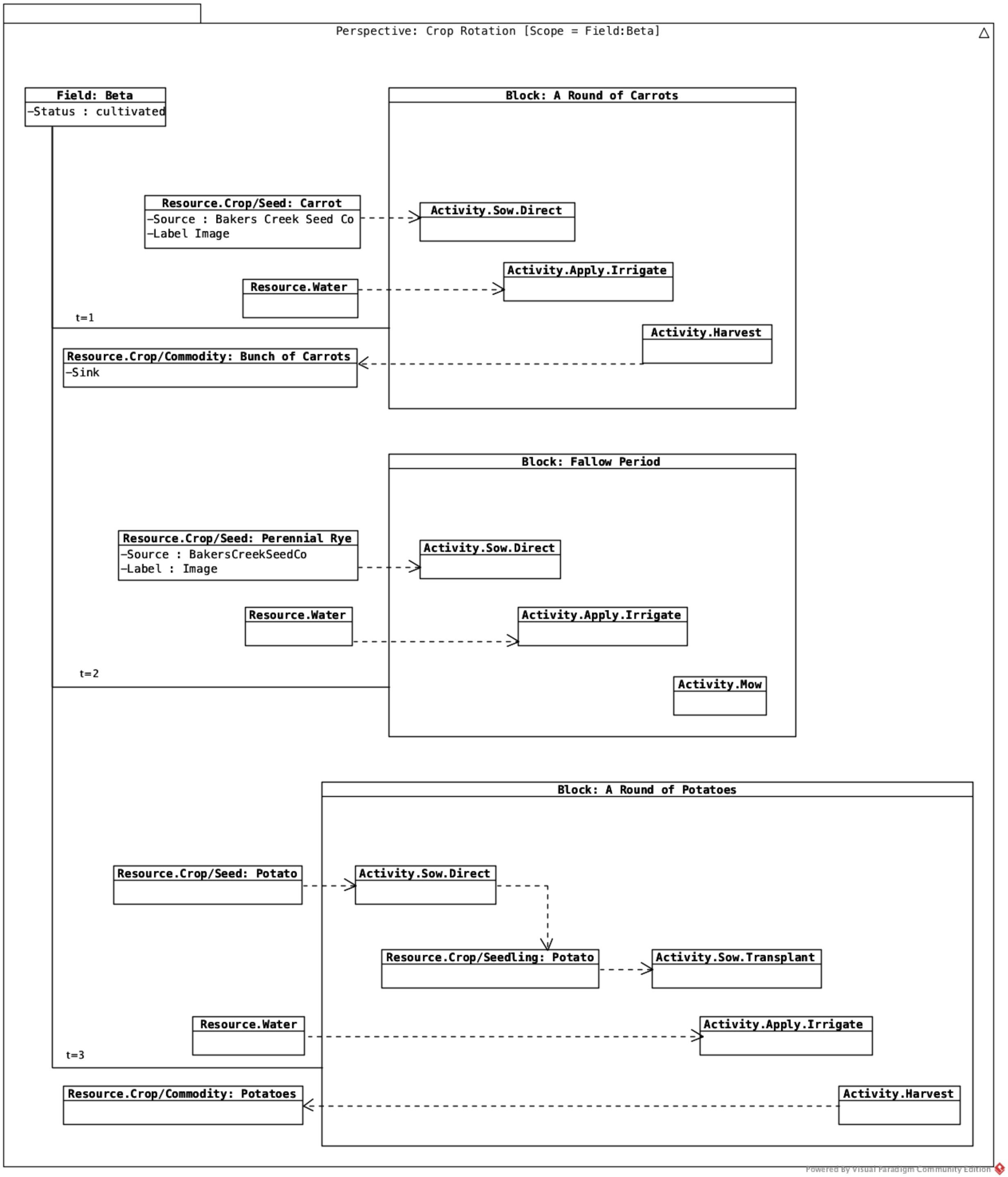


Figure 6.10: Blackbird Gardens: Field Beta: Crop plan, MoSS model.

6.2.3 Scenario Three: Environmental Stewardship

Prelude: A few miles west of Blackbird Gardens is the Salinas National Wildlife Refuge. The river on the southern border is part of a fragile habitat for many California birds, including the endangered Least Bell's Vireo [137]. With the influx of farms in the area, urbanization, and the impact of human existence, these habitats have been tarnished, at times even destroyed, leaving the local birds, flora, and fauna in danger [23].

Biodiversity is therefore an important element of sustainable agriculture [10]. The farmers at Blackbird Gardens act as stewards of the land and water. Part of being a sustainable farmer involves creating an environment conducive to the production of nutritious food, but that also serves as a habitat for native plants, insects, and animals. Farmers track the effects of their efforts to support local insects, wildlife, and plants, monitoring for effectiveness.

Given this, the farmers create a protected area on the southern border of the farm, the Riverside Forest *Field*. It their first attempt at providing a natural habitat for birds, in particular, the Least Bell's Vireo. This field serves as an indicator of biodiversity on the farm as a whole, but they have since integrated various invitations to nature across the farm.

The creation of this habitat has introduced some tensions on the farm, as predatory birds and animals are also attracted to the area [10, 23]. While there are benefits to the local environment, the farmers must be conscious of the effects of, for example, such predators on the crops, as well be sensitive to the immediate outflows of materials from the farm.

The Riverside Forest also contains a small Bed and Breakfast with a maximum single-booking capacity of 8 people to promote sustainable agriculture through agritourism. This provides both supplementary income for the farm, and an opportunity for the farmers to educate visitors about their environmental stewardship, promoting awareness of the role of nature in farming and the relationship of food and the wilderness [18].

Many of these farm elements may be characterized as "ecosystem services" [236] provided by Blackbird Gardens. These elements include: bird and bat boxes, bee-friendly gardens, beneficial and native crop plantings, and scenic landscapes for all forms of life to enjoy. Therefore, there are a variety of federal incentive programs to provide farmers with funding to participate in, for example, conservation stewardship programs [240]. The primary challenges in both participating in and demonstrating environmental stewardship practices involve quality assurance, the cost of information management, and coordination among stakeholders [184].

Scenario Goal: Assess environmental stewardship activities at Blackbird Gardens.

Walkthrough: Biodiversity data is collected opportunistically at Blackbird Gardens. Each of the farmers inadvertently collect data pertaining to environmental stewardship: whether it's Suraj taking a picture of a nesting bird (an image originally only headed to social media), or Harvey noting down native plants during a walk around the farm. Unless a farm is specifically participating in a research study, conservation program, or has some external reason for standardization, such environmental indicators are not collected in a formal manner.

While information about activities beneficial to nature (e.g., native tree plantings) or environmentally helpful objects on the farm (e.g. nesting boxes) vary in temporal scope, they are all valid indicators of the environmental stewardship practiced by the farmers. While the spotting of a single insect is not necessarily indicative of successful stewardship, creating and monitoring habitats, such as for native birds and insects, can result in more measurable improvements to the environment. Figure 6.11 (page 198) is overviews of some of types of data related to environmental stewardship at the Blackbird Gardens. These data can be represented using an Environmental Perspective on Blackbird Gardens as shown in the MoSS model in Figure 6.12 (page 199).

By combining these otherwise disparate data, the farmers at Blackbird Gardens can produce a detailed, evolving, and collaborative perspective on both their environmental stewardship practices and the local ecosystem. This allows the farmers to conduct the following activities:

- Apply for participation in National Resources Conservation Service's Environmental Quality Incentives Program (EQIP) [241]: The program requires agricultural producers to have a Conservation Activity Plan [243] demonstrating how farmers intend to engage in a specific form of environmental stewardship. For example, a California EQIP-eligible activity at Blackbird Gardens, is the creation of habitats for declining species, including birds and pollinators [242].

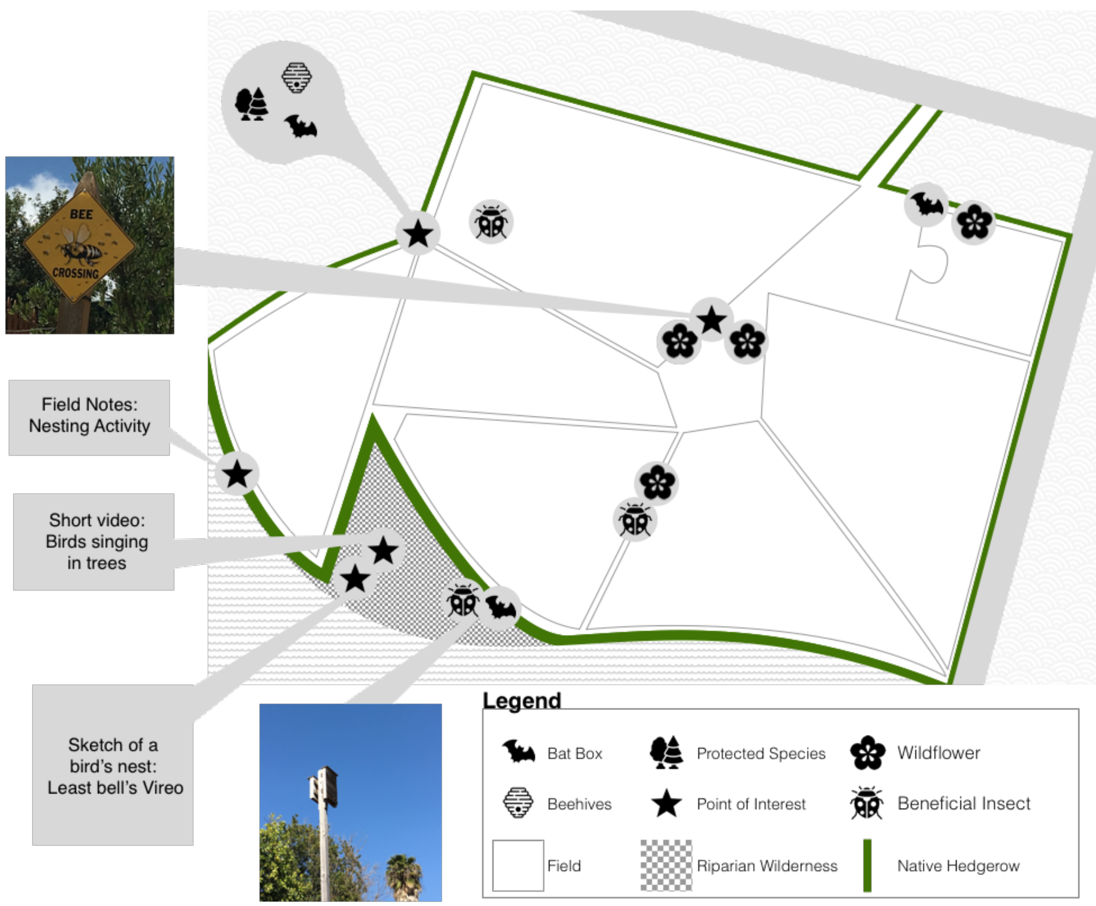


Figure 6.11: Blackbird Gardens: Observations of wildlife, protected areas, and other ecosystem services.

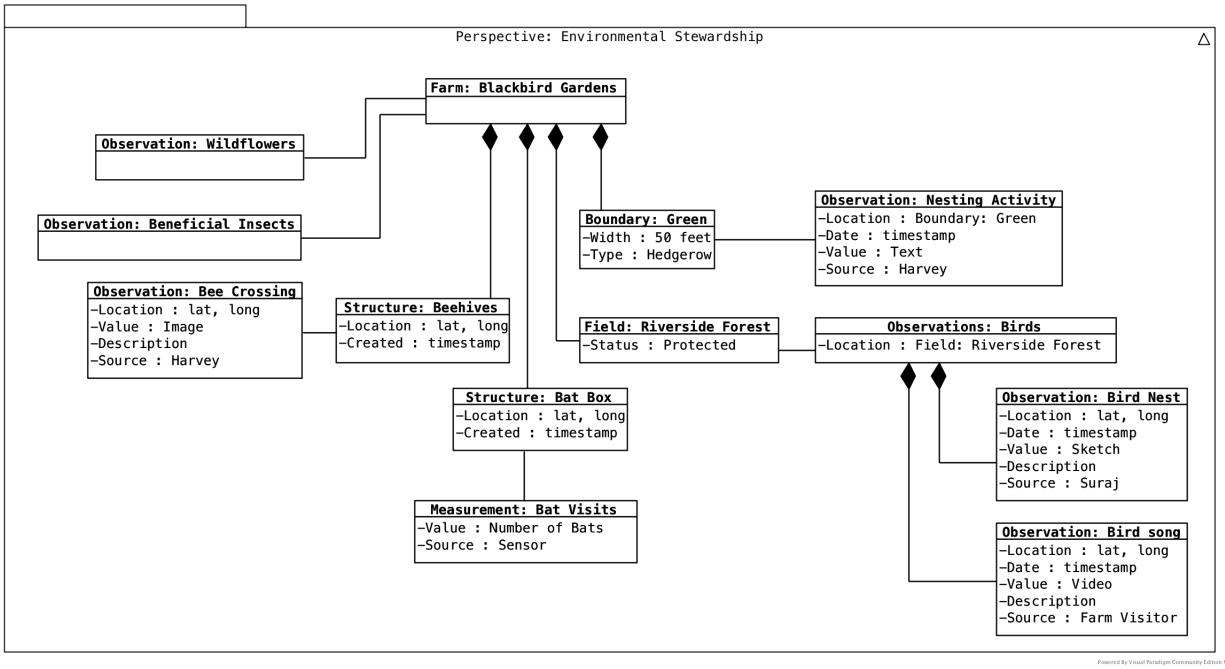


Figure 6.12: Blackbird Gardens: Environmental stewardship, MoSS model.

- Public awareness and citizen science: There is an opportunity for farm visitors to engage in the environmental stewardship of the farm. For example, visitors could collect data (as shown in the `Observation:Bird Song` in Figure 6.12) to assist in monitoring of protected areas.

- Comparing different initiatives: Through aggregation of environmental farm data, the farmers at Blackbird Gardens may be able to assess and compare the efficacy of various environmental initiatives. For example, exploring which types of Bat Boxes are more effective in their area or monitoring their activity to see if the locations are actually frequented by local bats or attractive to other birds instead.

6.3 Luna Orchard

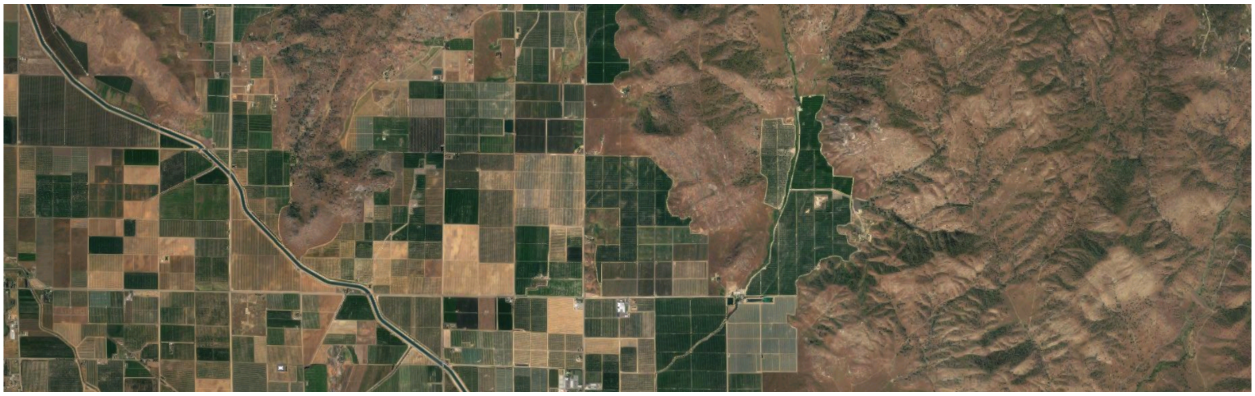


Figure 6.13: Luna Orchards: Geographical context.

Farm Overview: Luna Orchard is a 40 acre citrus farm located in the relatively conventional and highly productive San Joaquin Valley of California. Melika Singh has been farming in the shadow of the Sierra Nevada mountains for just over 10 years now. When she first bought the land, it was mostly covered in scrubs, and was surrounded by hundreds of acres of dense, conventionally farmed, citrus orchards. Melika considered presence of native plant growth an indicator of the capacity of the land. Further, as the farmland is uphill of the neighboring conventional farms, the potential for runoff contamination is low.

Since the 1930s, California has been responsible for an average of 25% of U.S. citrus production, with the the San Joaquin Valley leading the charge [84]. While the majority of citrus in the U.S. is produced conventionally, there has been an increase in the number of certified-organic citrus orchards [239]: this does not include the host of orchards that are engaging in sustainable practices but remain uncertified.

A variety of oranges, mandarins, and specialty citrus (mostly kumquats, citron, and loquats) are grown for sale at Luna Orchard. 20% of the land at Luna Orchards is protected wilderness, with only 32 acres actually planted with trees. Melika occasionally produces a small batch citrus preserves such as jams, jellies, liquors, and other value added goods.

The production of these is highly variable as it is mostly dependent on the distribution of fruit quality, demand, and time available. Melika keeps bees on the property, and while the honey is used in the value added goods from time to time, the bees are not kept on the farm commercially.

Farm Management: Melika is a the sole owner and operator of the Luna Orchard. She has two full time staff: one employee responsible for all sales and marketing, and another, who assists Melika with daily farm operations and record keeping. Seasonal workers are hired throughout the year to perform specific field work, from pruning to harvest, as is typical on farms in the area. Melika also works with a seasonal farm workers representative to help negotiate fair wages, benefits and increased work schedule predictability across several farms in the area.

Farm Sales: The crop commodities from the farm are sold through the following avenues:

- Farmers' Market: Produce is sold at one farmers market a week. Participation at this market is more for community and visibility.
- On-farm and On-line Sales: Jams, jellies, and other value added goods are primarily sold via e-commerce. Occasionally, people visit the farm as part of a farm tour, and both fresh fruit and citrus products made available for direct sale.
- Wholesale: the majority of fresh fruit is sold to a citrus cooperative that partners with sustainability-oriented grocery stores of varying sizes. Occasionally, a bulk order for value added goods is placed, but the farm is not productive enough for these to provide a financially stable income.

Farm Goals: Creating a pocket of wilderness and organic growth in this complex landscape is one of the major challenges faced at Luna Orchard. The neighboring land-use is mostly high-intensity orchards where the trees are densely packed and the both water and material inputs are high. As a sustainability-oriented farm, it is vital that effective buffers are created between the orchard and its neighbors, protecting the trees from groundwater contamination and aerosol spray contamination, while encouraging a diversity of weeds, insects, and other organisms [60]. Communicating effectively with her neighbors has been the cornerstone of Melika's success in farming sustainably in the region.

At Luna Orchard, Melika is dedicated toward creating a farming system that is as natural and self-sufficient as possible. Goals include:

- Protect the farm from ongoing crop- and location-specific pests and diseases.
- Collaborate with neighboring farmers to transition to sustainable agriculture
- Investigate how water flows within the farm boundaries to optimize water use.
- Focus on product quality, resilience, and soil health.

6.3.1 Scenario One: Multilayer Layouts

Scneario Goal: Describe the structure of Luna Orchard.

Walthrough: Consider first, the layout diagram of Luna Orchard in Figure 6.14. While the land was purchased 10 years ago, Melika planted groups of trees in stages, resulting in four major fields, each of a different age as annotated in the farm layout diagram. The fields were named after the primary tree type: the Mandarin Field consists of several varieties of mandarin trees; the Lemon Fields contains two varieties of Lemons; the Orange Field is mostly Navel Oranges; and the Specialty Field contains a mix of rare citrus.

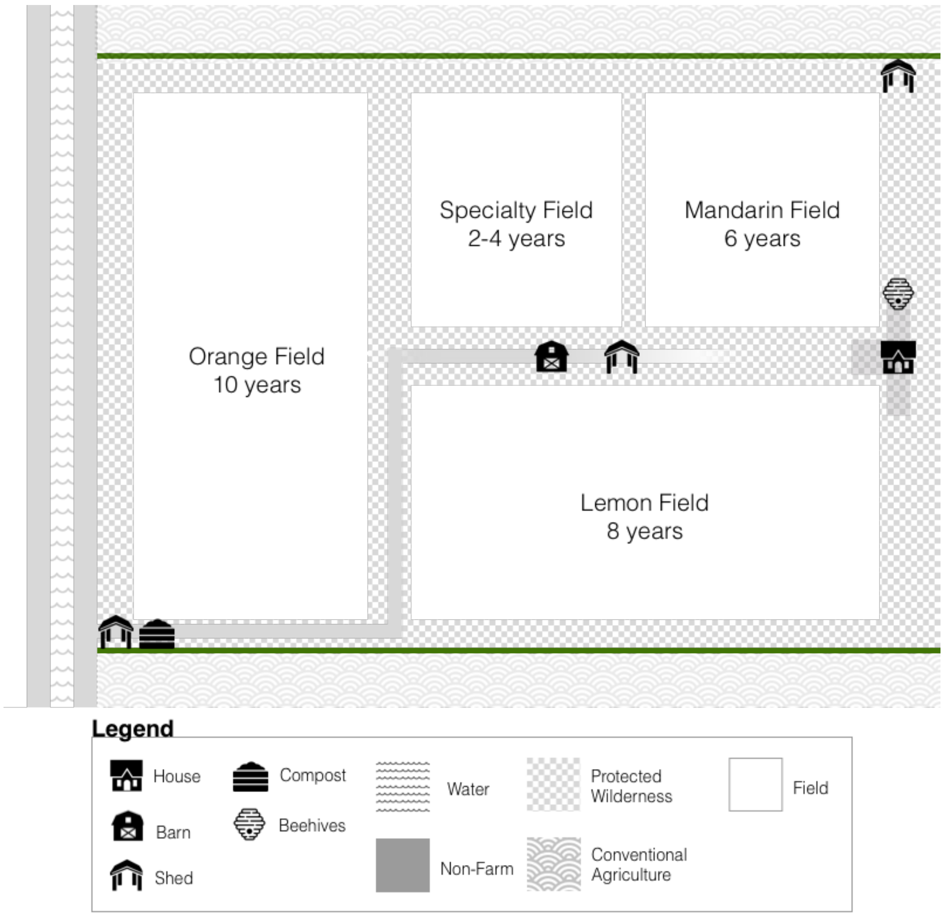


Figure 6.14: Luna Orchards: Layout diagram.

Next, consider a one-acre subsection of Field Mandarin, shown in Figure 6.15. This field been planted in a rectangular grid layout, with the rows spaced wider than the trees. Cover crops are planted between each row, in what is colloquially called the "row middle" [118].

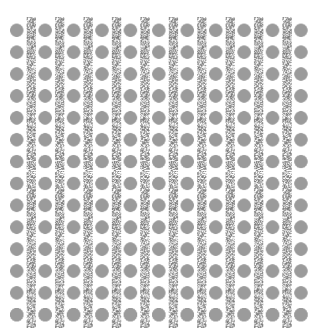


Figure 6.15: Luna Orchards: Field Mandarin: Layout per acre.

Cover cropping is a core practice in sustainable agriculture. It improves soil fertility and protect the soil from erosion; reduces water loss due to evaporation; and, depending on the cover crops planted, can provide nutrients for the trees and habitats for beneficial insects [158]. The mixture of cover crop is one that Melika has developed to complement the local environment, supplement missing nutrients, and to maintain soil health. It is refined as Melika compares tree health and productivity with soil health and the cover crops used.

A MoSS model representing the field layout of `field: MANDARIN` is shown in Figure 6.16 (page 204). This field has two associated layers: `layer: TREE`, and `layer: COVERCROP`. `layer: TREE` contains a set of Mandarin Trees planted in grid layout with a tree spacing of 13 feet and a row spacing of 23 feet, with rows being oriented North to South. This results in approximately 11 rows with 14 trees per row, and approximately 154 trees per acre. This pattern is repeated over the full 5 acres on this field. Cover crops are also planted on the same field in a row layout of approximately 23 feet between rows.

Figure 6.16 shows the layered layout of the Mandarin Fields.

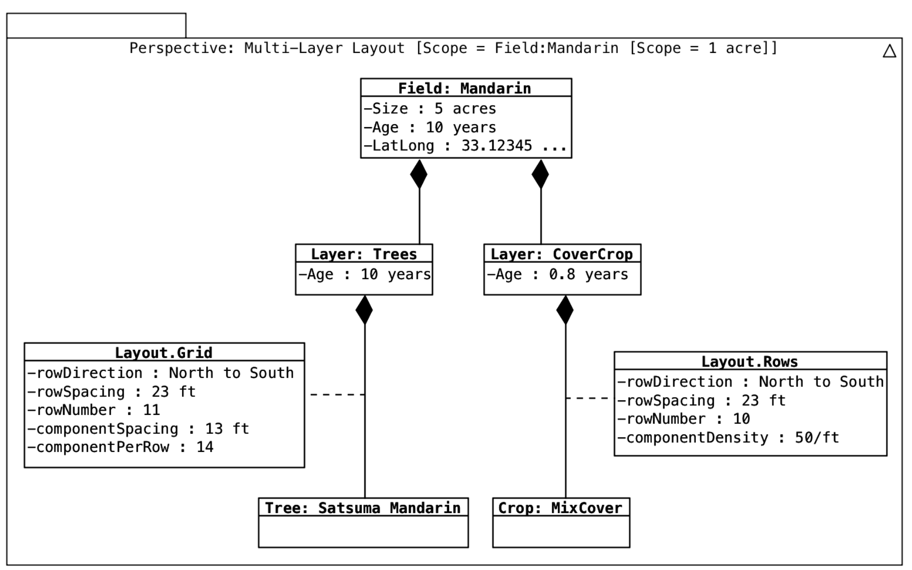


Figure 6.16: Luna Orchards: Field Mandarin: Layout per acre, MoSS model.

field: SPECIALTY can be similarly represented (Figure 6.17, page 205) using MoSS. It is an open field on which trees have been planted opportunistically, to create a garden like atmosphere. Thus the trees are not planted in a predictable grid, but in an open layout, where each tree is identified by it's latitude and longitude.

Similarly, Figure 6.16 shows the layered layout of the Specialty Fields.

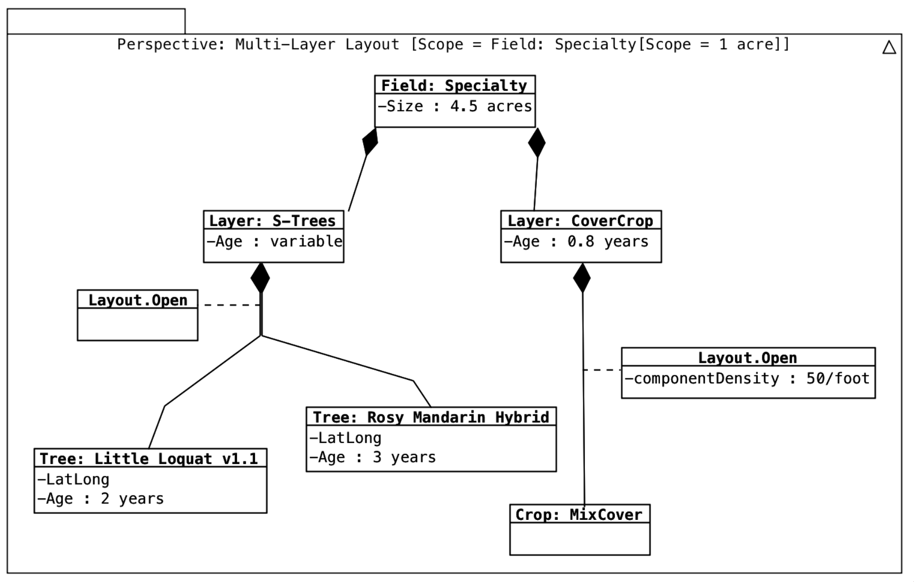


Figure 6.17: Luna Orchards: Field Specialty: Layout per acre, MoSS model.

6.3.2 Scenario Two: Diagnosing a Tree

Prelude: Huanglongbing (HLB) is a citrus disease that causes stunting, deterioration, and eventually death of the tree [33]. HLB is transmitted by the Asian citrus psyllid (ACP)- a small plant-feeding insect [91]. Since 2005, the American citrus industry has been adversely affected by HLB as it first spread through Florida [106], and more recently, California [34]. There is no known cure for HLB: current treatment and disease management involve monitoring, reporting, and reduction of the psyllid vector through the application of appropriate insecticides [35].

Quarantine zones have been set up by the California Department of Food an Agriculture as shown in the Figure6.18 below. This means that all parts of the citrus tree including leaves and stems cannot be transported outside these zones. The citrus fruit itself must be cleaned of leaves and stems and disease-free prior to external transport [33].

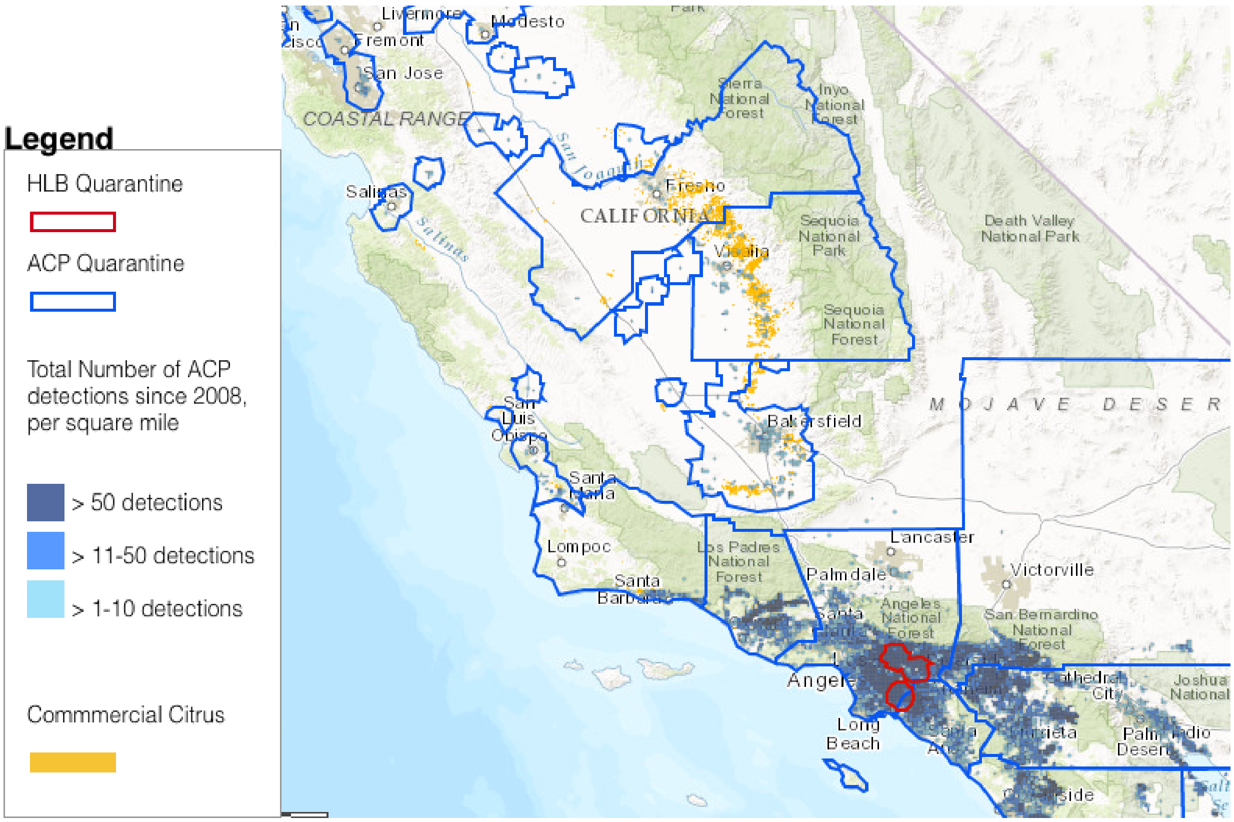


Figure 6.18: Luna Orchards: Surrounding quarantine zone [34].

Constant vigilance is of utmost priority. The University of California Co-operative Extension advisors recommend monitoring one's orchard for any signs of ACP presence, from eggs to adult psyllids, as well as monitoring tree health for any symptoms [220]. The issue is complicated by the difficulty of spotting psyllids and as the symptoms of HLB are reminiscent of nutrient deficiencies [33]. Depending on psyllid sightings, orchards are subject to a variety of restrictions, such as, specific integrated pest management programs, local ACP eradication programs, and assignment of HLB quarantine, depending on severity [35].

Scenario Goal: Capture information related to orchard, field, and tree health.

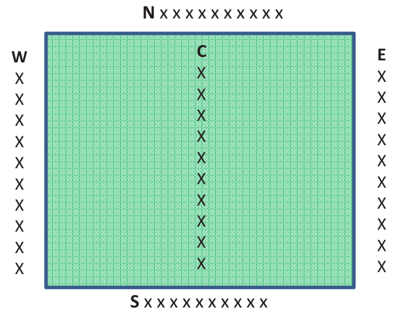
Walkthrough: While none of the trees in Luna Orchard currently suffers from HLB, the farm is located in an ACP Quarantine Zone, and is in close proximity to other citrus orchards with low-level psyllid sighting (see Figure 6.18). Melika decides to engage in a more rigorous monitoring program based on the guidelines recommended by the University of California Statewide Integrated Pest Management (UC IPM) program [35].

Data collection techniques are used for ACP monitoring at Luna Orchard are:

1. Visual Survey: One young leaf per sample tree is visually inspected for presence of psyllids at all stages (eggs, nymphs, adults) [220].
2. Tap Sampling: A sample tree repeatedly sprayed with a soapy mixture, then shaken onto a plastic-covered clipboard surface. If present, adult winged pysllids are trapped by the liquid and fall onto the surface to be counted and recorded [220]. Figure 6.19 (page 208) shows a UCCE worksheet for conducting tap sampling.

These data are supplemented by Melika's other tree-health related data collection, (as marked on the diagram in Figure 6.20):

3. Problem Tree: Melika notes any issues she may notice with a tree. This includes discoloration, errant growth, or other anomalies. This is typically the beginning of a deeper investigation into a tree.
4. Tissue Samples: Plant tissue is sampled to assess effects of fertilization or diagnose health issues in the tree, such as nutrient imbalances. Approximately 10 trees per block (5-10 acres) are sampled [130].



University of California
Agriculture and Natural Resources

Asian Citrus Psyllid Sampling plan

Monitored by: ____________________ Date: ___________

Orchard name: ___________________ Leaf status (circle one): feather flush/growing flush/fully expanded

Block name or number: ________________ Variety: ___________ GPS: ___________

Instructions:

1. Sample 10 trees on the north, east, south, west borders rows/trees of the orchard and in the center of the orchard.
2. Hold clipboard with white paper under a branch and strike the branch 3 times, counting the total number of winged adult psyllids per 3 taps.
3. Examine one young flush per sample tree. Count and record the number of eggs, nymphs and adults found on each flush examined (E/N/A).

North trees	#ACP/ tap	#ACP/ flush E/N/A	East trees	#ACP/ tap	#ACP/ flush E/N/A	South trees	#ACP/ tap	#ACP/ flush E/N/A	West trees	#ACP/ tap	#ACP/ flush E/N/A	Center trees	#ACP/ tap	#ACP/ flush E/N/A
N1			E1			S1			W1			C1		
N2			E2			S2			W2			C2		

Figure 6.19: ACP Tap sample worksheet [220].

5. Pest & Weed Sightings: If problematic pests or weeds are sighted, Melika tries to either take a photo, or write down some observations regarding the conditions of the sighting.

6. Sample Productivity: During harvest, tree productivity is also sampled to keep track of how much fruit is being produced in different areas of the orchard.

Figure 6.20 (page 209), is an overview diagram of such data collected over a 1 acre subsection of Field Mandarin in the past year. While each of these data are typically recorded independently, Figure 6.21 (page 209)demonstrates how by layering these data, one may be able to identify a problematic area that warrants an investigation. This is marked in a grey circle on the diagram.

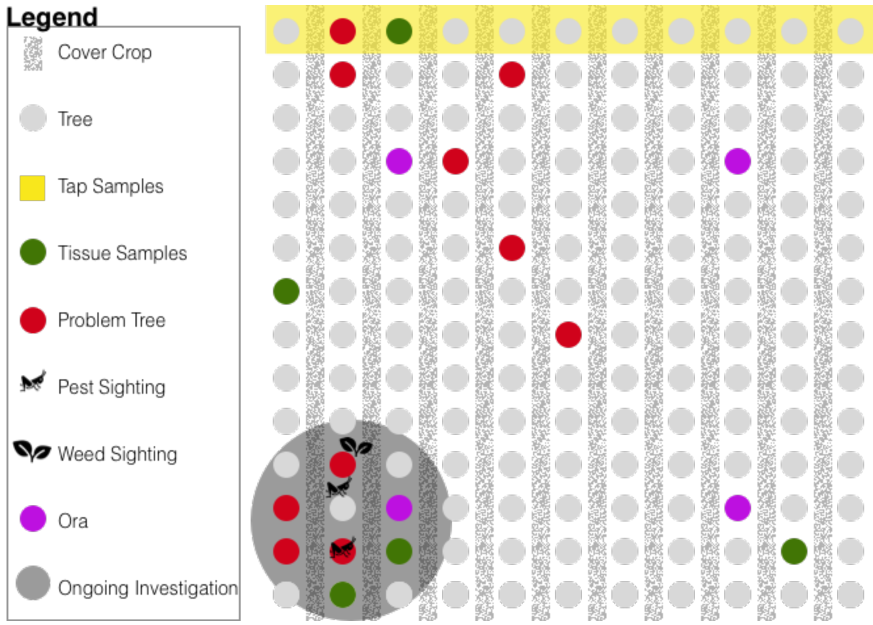


Figure 6.20: Luna Orchards: Field Mandarin: Tracking problem areas.

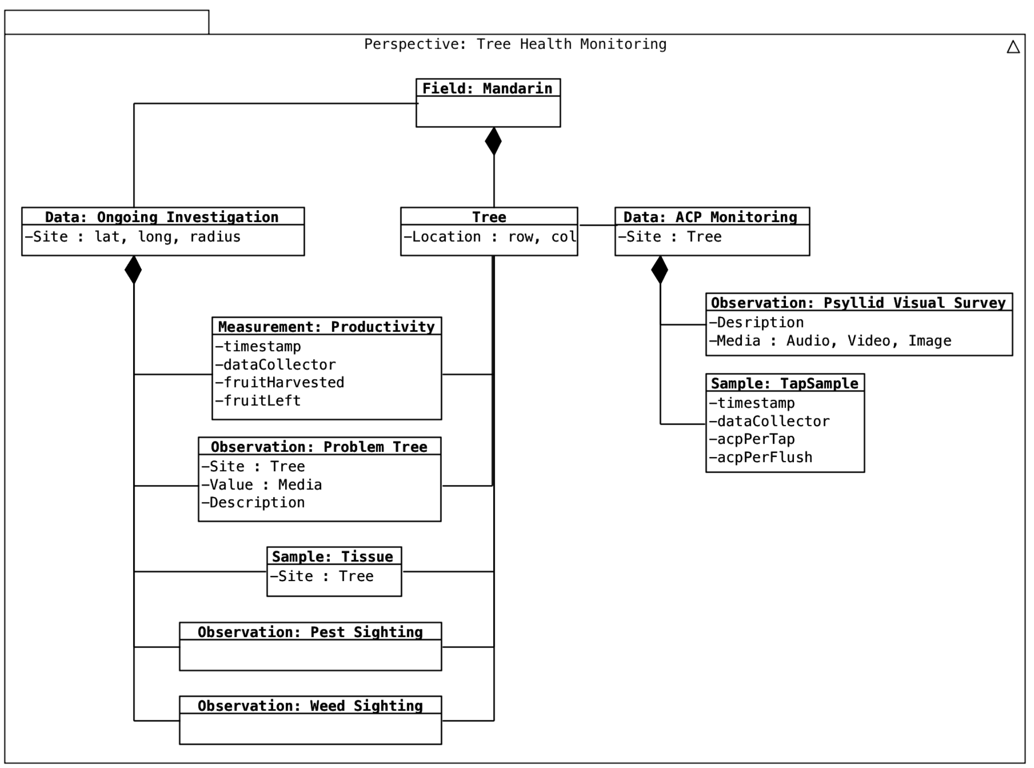


Figure 6.21: Luna Orchards: Field Mandarin: Tracking problem areas, MoSS model.

By representing these disparate data in a MoSS, Melika can engage in the following types of activities:

- Layer symptom data: There is potential for gaining deeper insights into seemingly unrelated issues on a farm. For example, when a tree in a particular spot dies, it is often replanted. If trees planted a particular spot keep dying, there may be other environmental factors that need to be explored.
- Compare intervention effects: as she tries various controls to deal with tree health issues and collects similar data throughout treatment, Melika can monitor the effects of each treatment throughout the farm. During a typical meeting with an Integrated Pest Management (IPM) representative, a farmer would present whatever data they have about the issue at hand, as well as any records regarding previous interventions. A consistent and changeable farm model across IPM visits during a treatment, may also allow for the farmer and representative to engage in collective monitoring and reflection over the treatment effects. This process would allow for refinement of the responses to various diseases, pests, and weeds.
- Shareable model: By having a coherent model of weed, pest, and disease related information about the farm, it would be possible to provide the CDFA with farm-level data about ongoing tree-health events that may augment their understanding of how, for example, the psyllid vector moves.

6.3.3 Scenario Three: Tracking Water

Prelude: Water is a critical resource on a farm [158]. It is used to irrigate crops, feed animals, wash and process farm products, and for use in other on-farm activities. At Luna Orchards, water is primarily used for tree irrigation[1].

Luna Orchard is located within the Kings River watershed in the Central Valley of California. It is claimed to be one of the "largest and most complex water storage and conveyance systems in world" [189]. Drought notwithstanding, water availability has always been a concern in the area resulting in complex water infrastructure [117].

Melika estimates the orchard's water requirements and purchases the appropriate amount of water from one of the many local water purveyors. Based on water availability (among other restrictions), water is released according to her purchase, and travels through various components of the local water conveyance systems [189], finally arriving at the irrigation ditch located on the western border of Luna Orchard, (marked on Figure 6.22, page 212). Melika is then required to turn on the farm's water pumps to let the water out and into the farm boundaries. Water is technically an input resource to the farm at the moment of purchase: if the pumps are not opened, and the water overflows or simply follows the ditch trajectory, it is still considered sold.

Once the pumps are opened, water flows onto the farm and is now available for tree irrigation and other agricultural purposes. To supplement this water supply, Melika has a water-well, like more and more farmers in the Central Valley [148]. However, well-water quality in the area surrounding the orchard has to the surface water coming in, therefore, there is a preference for using surface water when available.

[1] Water use on the homestead, farmer's personal garden, beehives, and other non-cultivation water use is not considered in this scenario.

Two types of micro-irrigation systems are used at Luna Orchards. The older fields, Orange and Lemon, use a drip irrigation system that require point-source emitters. This method of irrigation has been commonly used on Orchards since the 1970s, as it allows for specific water delivery, is energy efficient, and can easily be automated [100]. The two newer Fields, Specialty and Mandarin, use micro-sprinklers. While these are more prone to damage, they disperse water over a larger radius, allowing for a greater root area to be irrigated [100].

Figure 6.22 (page 212) is an overview of the water infrastructure at Luna Orchards. It shows two metered pumps located by the irrigation ditch, major pipes conveying water between fields, 6 valves to control water flowing to subsections of each of the fields, and a water well. It does not show many other features of the farm's water infrastructure including pressure gauges, water filters, injectors (to add other inputs to the water supply), or the individual lines conveying water to each of the trees.

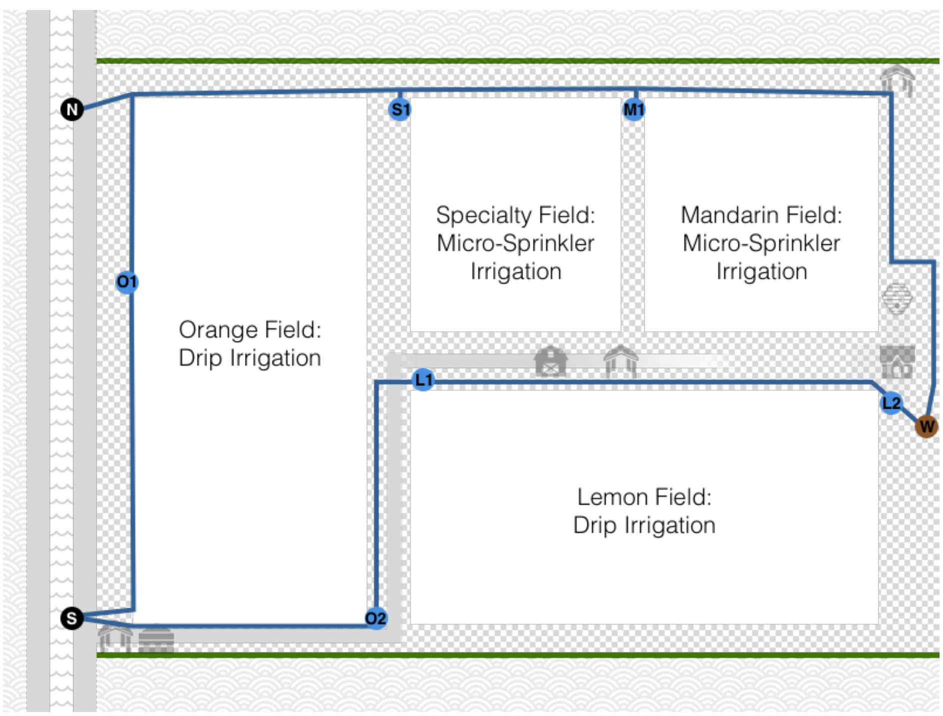


Figure 6.22: Luna Orchards: Water infrastructure.

The MoSS model in Figure 6.23 (page 213) similarly represents the water infrastructure at Luna Orchard.

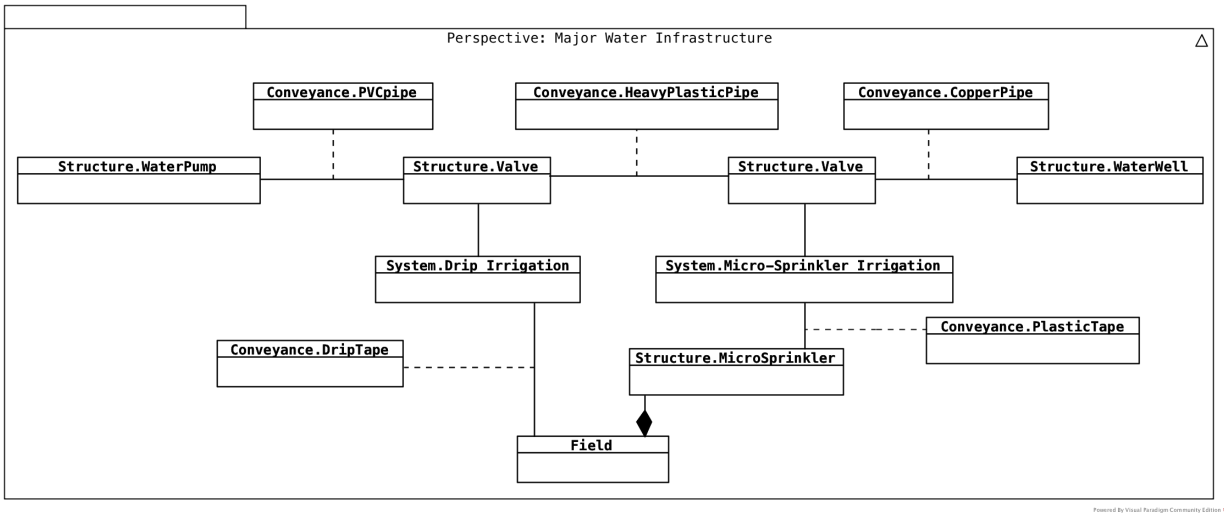


Figure 6.23: Luna Orchards: Water infrastructure, MoSS model.

At Luna Orchard, water quantity is calculated via meters located at the pumps, well, and particular field-level valves. Water quality is monitored via:

- Reports provided by external organizations including: Kings River Watershed, Luna Orchard's water purveyor, and the local ditch company.
- Samples periodically taken at various points through the irrigation system (pumps, filters, field-level valves, etc.). These samples are either sent to an external lab, or tested using at-home kits depending on the sophistication of the test being conducted.
- Melika also records environmental observations as indicators of water quality.

These flows of water and associated data can allow for Melika to gain various perspectives on the agricultural system. Each of the data types collected can be associated with various components of the farming system.

This MoSS model can allow for the tracking of how water flows in, around, and out of a farm. Melika can explore each of these types of flows:

- Track water entering the farm to calculate how much water is being used, calculate the water footprint of the farm, and to monitor water quality.
- Track water moving inside a farm to gain insights into the efficacy and efficiency of the different irrigation systems and to assess crop supplement needs based on water composition.
- Track water exiting the farm to monitor pollution carried in water and the effect of outflows to external water systems (e.g. local aquifers), as well as for reporting to the Irrigated Lands Regulatory Program [200].

6.4 Maribel Farms

Figure 6.24: Maribel Farms: Geographical context.

Farm Overview: Maribel Farms is an integrated sustainable family farm that has been run by the Smith family for 50 years. Jacob Smith, a fifth generation farmer is currently at the helm of Maribel Farms, with his son Ash working closely with him as an apprentice. The portfolio of crops grown, animals raised, and goods produced at Maribel Farms is atypically diverse. The farm contains pastures for livestock and poultry, orchards for fruit, tens of acres of seasonal vegetables, grains, and legumes, and buildings for creating value-added goods.

These agricultural subsystems are spread across two non-contiguous properties. The primary farm property is 100 acres of mixed farmland on the outskirts of the city of Davis, in Yolo County, California. The older, now secondary farm property, is a 50 acre parcel located on the banks of the Sacramento river, where the farmers have recently begun transitioning orchard fields to aquaculture ponds.

While Maribel Farms has been an exemplar of organic agriculture since its foundation, it are not an entirely certified organic operation: only a small subset of products have bee certified through California Certified Organic Farmers (CCOF) since the mid-90s. Instead, the Smith family practices sustainable agriculture through a holistic systems approach.

As an *integrated* farm, the farmers try to minimize the number of inputs and outputs to the farm. The farmers closely monitor of the effects of their farming activities on the natural environment, and actively adopt those that are beneficial to the local environment, such as: cover cropping, low-till, and use of biological controls.

There is also a focus on creating closed resource loops. For example, waste water from one activity (e.g. aquaculture) is treated and used for another (e.g., irrigating orchards). Further, energy is produced on-site through solar panels and biomass generators that utilize excess organic materials and waste.

Farm Management: While Jacob is the primary farm manager, several members of the extended Smith family are involved in farming operation: from Mary (his sister-in-law) who runs the farm office, to Jeremy (his cousin's stepson) who manages the livestock. This vast network of engaged family members must work closely with one another to ensure that the complex operations at Maribel Farms run smoothly. To supplement the farm's labour requirements, full time farm workers are employed, with each person performing multiple types of activities throughout the year.

Farm Sales: A variety of crops, animal products, and value-added goods produced at Maribel Farms are sold through the following avenues:

- Community Supported Agriculture (CSA): The farms primary income is through a small but dedicated group of CSA members, many of whom have been with Maribel Farms for several years.
- Farmers' Markets: The Smith family participates in a selection of farmers' markets, primarily to drop off CSA shares and market the program. Excess goods are also sold at these markets.
- On-line Sales: Maribel Farms has an online presence predominantly for marketing, brand awareness, and consumer education. There is currently a basic CSA management tool integrated into their website that allows members to view their CSA membership details, plan and pause deliveries if needed, and get more information on foods in their upcoming shares.

Farm Goals: At Maribel Farms, the focus is on low-input farming and managing the full life cycle of goods. The farmers pay close attention to the impact of their farming practices on the integrity of the land ecological indicators of environmental health.

- Conduct data-driven experimentation in sustainable agriculture.
- Streamline record keeping related to organic certification.
- Capture institutional knowledge to pass down the generations of farmers to come.

- Focus on food diversity and quality, soil health, and yield improvement.

6.4.1 Scenario One: System of Systems

Scenario Goal: Describe the structure of Maribel Farms.

The CSA program at Maribel Farms is *depth oriented*. This means that the farmers aim to provide a small group of CSA members with as much of their food as possible. This includes vegetables, fruits, meat, fish, poultry, grains, legumes, and even some minimally processed goods staples like milled grains, pickled vegetables, and fruit jams. Their goal is to sustainably produce complete diets for entire families.

To produce this range of commodities, there are multiple cultivation systems: orchards, vineyards, row crop fields, open fields for cultivation of rice and grains. Each of these cultivation systems are geographically spread across the farms. For example, the stone fruit trees are not clustered in one field, instead, they are planted in the boundaries between each of the major row crop fields. Further, once trees are mature, animals are allowed to graze the cover crop in these boundary fields. Fields containing row crops are rotated between vegetables, nutrient-intense ground fruit like strawberries, and field crops like legumes and grains.

The various groups of of animals raised on the farm are also treated as systems unto themselves. Chickens are raised in mobile coops that are moved to fallow fields, and are let loose to feed on excess and unharvested crops in fields once a harvest periods are complete.

Finally, the farmers try to both produce as many of the resources they need as possible, as well as reuse waste on the farm. For example, there are extensive composting sites on the property, typically at the center of fallow fields to allow for both the resulting organic matter to be spread across the field once it is done.

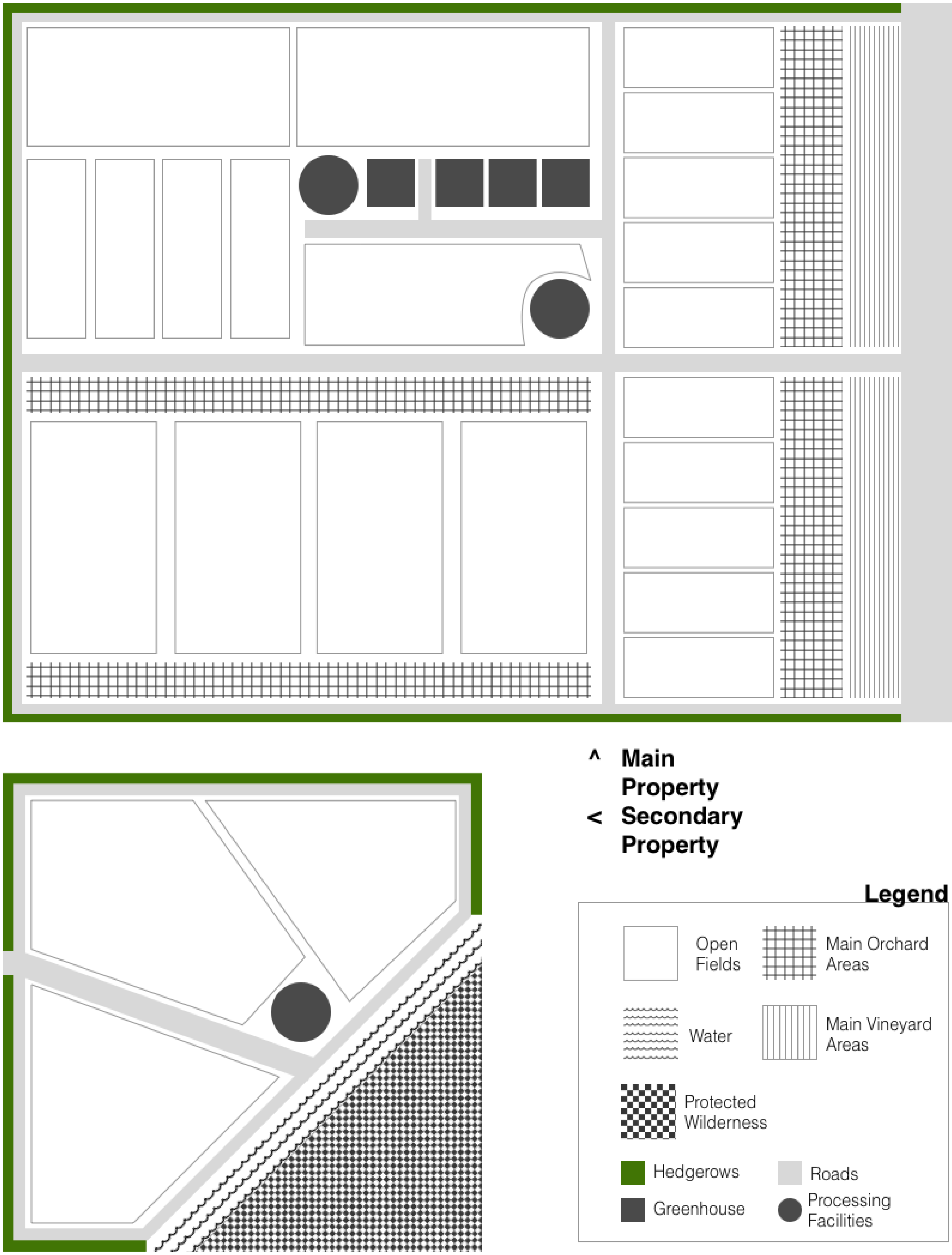


Figure 6.25: Maribel Farms: Farm layout.

This multitude of systems has resulted in a dynamic and complex farm layout and structure at Maribel Farms. The Smith family farmers do not use a detailed map, opting instead for a simplified layout diagram as shown in Figure 6.25 (page 218).

Maribel Farms can be characterized as a *system of systems*. This can be modeled using MoSS as shown in Figure 6.26. A systems modeling approach is used to obfuscate the details of each of the systems that are not necessary when simply considering the high level structure of the farm.

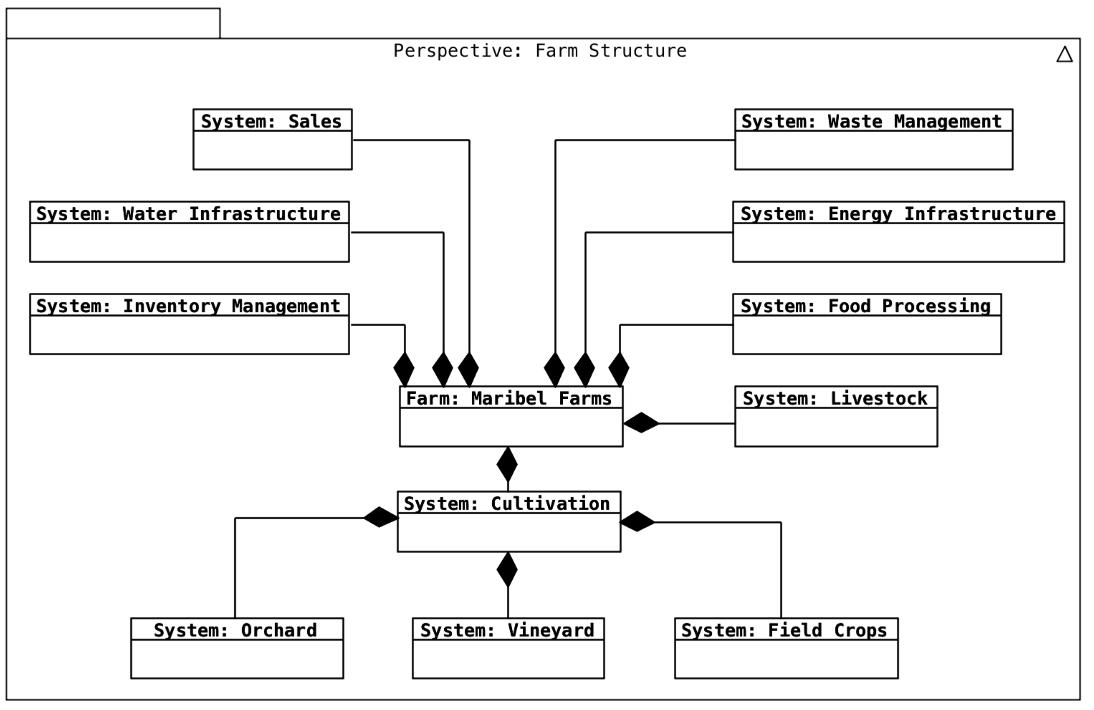


Figure 6.26: Maribel Farms: Farm layout, MoSS model.

6.4.2 Scenario Two: Organic Certification

Prelude: In response to a growing interest in sustainable agriculture and a demand from consumers for transparency in the food chain, a host of food labels have been created (e.g., [231, 44, 58]). Each of these are governed by their own certifying organizations, are subject to varying levels of ambiguity or specificity, with enforcement ranging from fancy to regulator, and have resulted in niche communities of practice.

The term *organic*[2] has grown to become synonymous with sustainable agriculture. The spectrum of sustainability in agriculture is indeed broader than what is specified by the United States National Organic Program (NOP) [231]. Nevertheless, the certified-organic movement is a compelling example of the role and effect of an explicitly specified assessment on sustainable agriculture.

In the 1990 Farm Bill, the United States federal government enacted the Organic Food Productions Act (OFPA) to enable the standardization of the production and handling of certified-organic foods [131]. This act resulted in the National Organic Program (NOP) that enables the implementation of the provisions of the Organic Food Productions Act [231] through the associated NOP federal regulations [223]. The NOP standard defines "organic production" as:

> "A production system that is managed in accordance with the [Organic Food Productions] Act [of 1990, as amended,] and regulations in this part to respond to site-specific conditions by integrating cultural, biological, and mechanical practices that foster cycling of resources, promote ecological balance, and conserve biodiversity." [223]

The specific production and handling practices required by an agricultural system to comply with the NOP depend on the types of crops cultivated, animals raised, and goods produced.

Table 6.9 summarizes NOP regulations [223] applicable to crop agriculture [3].

[2] In this dissertation, I differentiate between the word *organic*, and "organic certification indicating compliance with the U.S National Organic standard" [231] by referring to the latter as *certified-organic*.

[3] As recommended by Quality Certification Services (QCS), an organic certifying agency [177].

Table 6.9: Summary of selected NOP regulations [223].

Subpart	Description
§205.201	Organic System Plan: A farm must have an plan describing agricultural and record keeping practices, and all resources that are used in products to be certified-organic.
§205.103	Record keeping: A minimum of five years of records must have been kept prior to certification. This includes activity logs, resource input application logs, production records, seed and seedling invoices, and labels of input purchases.
§205.105	Allowed & prohibited substances: A farm must comply with the list of allowed and prohibited substances. Any deviation from the list results in loss of certification.
§205.202	Land requirements: Only NOP-compliant substance can have been applied to the land for a minimum of three years prior to certification. There is are provisions for transitional certifications if a farm has not yet been NOP-compliant for three years.
§205.203	Soil Fertility and Crop nutrient management practice standard: Agricultural practices must include activities related to improving soil fertility and nutrients in crops. Examples include: crop rotation, appropriate tillage levels, and the use of cover crops.
§205.204	Seeds and planting stock practice standard: Seeds and other crop stock purchased must also be organic-certified. There are certain exceptions, e.g., crops for which there do not exist readily available certified-seeds, but these require additional documentation.
§205.205	Crop rotation practice standard: Crops must be rotated through some management process to improve soil, plant, and environmental health.
§205.206	Crop pest, weeds, and disease management practice standard: physical (e.g., trapping, mowing) and cultural practices (e.g., sanitation, appropriate plant selection) must first be used to manage pests, weeds, and diseases. In the event the these are not successful, only allowed substances can be used in the farm.
§205.300-205.311	Labeling: NOP labels and terminology are subject to labeling requirements. For example, the term *100 percent organic* can only be used if all ingredients and resources used are also 100 percent organic. If 95 percent or more of the ingredients are certified-organic, then the term *organic* may be used.

Typically, a small- to medium- scale farmer enlist the services of one of the many third-party certifying agencies [228] (that in turn must be NOP-certified certifiers) to demonstrate NOP compliance and obtain certification. While each agency has to adhere to the standard laid out in the NOP, there are degrees of flexibility with respect to data collection and reporting formats, inspection techniques and practices, program guidance, and financial assistance available.

Each crop on each field must be evaluated for compliance. In an agricultural system with diverse crops grown, it is possible to have, for example, the grapevines in one field certified organic and another field non-compliant and therefore not certified. This means that the crop from the two fields would have to be processed, handled, and treated separately for the compliant-field grapes to be certified-organic. The complexity of the farm therefore determines the complexity of the certification process, and even the cost of certification [16].

Scenario Goal: Represent relevant aspects of Maribel Farms to assess field crops' compliance with the National Organic Program.

Walkthrough: Let us now consider three examples of how MoSS models of Maribel Farms can be checked for compliance with the NOP, given that only field crops are to be certified-organic.

Part 1: Using `farm/components` to represent land use. The standard for land use (§205.202) requires "distinct, defined boundaries and buffer zones such as runoff diversions to prevent the unintended application of a prohibited substance to the crop or contact with a prohibited substance applied to adjoining land that is not under organic management" [223]. This requirement would subsequently be interpreted by a certifying agency to be more specific and allow for a farm to be evaluated[4]. For example, this could be interpreted to require a minimum 30 foot boundary between the land in which the crop to be certified is grown and any conventionally farmed land.

At Maribel Farms, orchards and vineyards are planted in the borders, creating productive buffers in the boundary between the farm and the world, as well as between fields. For example, the perimeter of the the main farm property consists of two separate boundaries, a `boundary: WEST` is a planted vineyard that separates the farm from a road and conventional agriculture beyond. Note, because this vineyard is planted in the buffer zone, even though it meets all other requirements to be certified-organic, any harvested grapes can only be sold as conventional grapes. If they are to be certified-organic, the vineyard would need its own 30 foot buffer. The second boundary, `boundary: GREEN`, runs along the rest of the farm perimeter, and consists of native trees and bushes planted to both act as a farm buffer, but also to provide an habitat for local wildlife, insects, and plants.

Figure 6.27 is spatial perspective of Maribel Farms showing the `components` and `boundaries` that would need to be checked for NOP compliance at Maribel Farms.

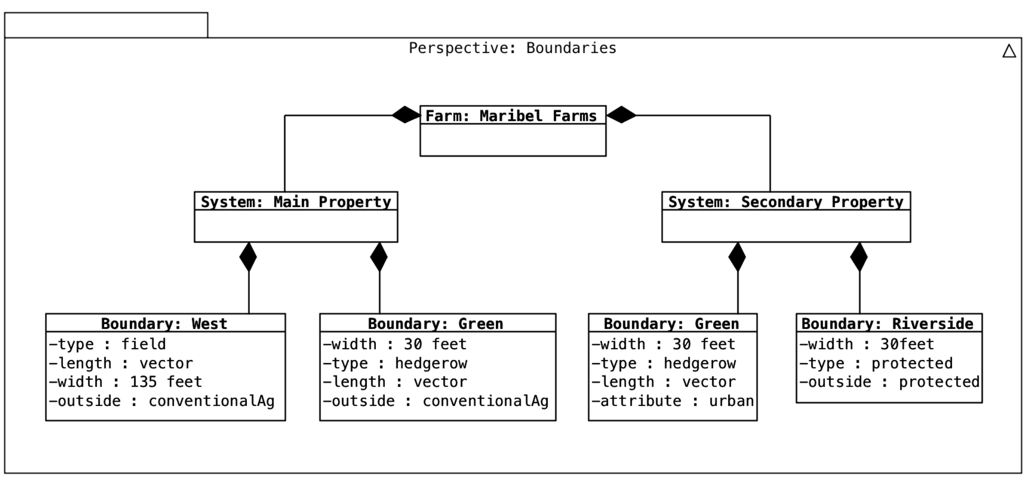


Figure 6.27: Maribel Farms: Farm boundaries, MoSS model.

[4] In this dissertation, I consulted both CCOF [32] and QCS [177] documentation for examples of how the NOP is instantiated.

A MoSS Perspective is created and evaluated for compliance with the NOP using the following model checking condition:

NOP Condition 1 - Boundaries

```
farm: MARIBEL = perspective.assessment/condition: BOUNDARIES
  perimeter = filter (fields, boundaries),
              where (boundary[outside] == conventionalAg)

  for (boundary in perimeter):
    if (boundary[width] >= 30):
        farm : MARIBEL [certified.organic] = true
    else:
        farm: MARIBEL[certified.organic] = false
```

Part 2: Using `farm/activities` to represent agricultural practices. Several NOP subparts require information that is captured through some form of activity log. For example, information about field activities is required for NOP subsections §205.204, regarding soil fertility and crop nutrients). In particular, there are requirements regarding the management of "plant and animal materials to maintain or improve soil organic matter content in a manner that does not contribute to contamination of crops, soil, or water by plant nutrients, pathogenic organisms, heavy metals, or residues of prohibited substances" [223].

Consider the production of the `crop:` WHEAT in the `system:` FIELD CROPS in the `farm:` MARIBEL FARMS; if the wheat is to be certified-organic, all activities relating to the wheat production must meet NOP requirements. There are two types of soil amendments that Jacob applies to the field: animal manure, and plant-based compost.

1. Raw animal manure: First, animals are allowed to graze on the field, feeding on leftover crops and weeds, and producing manure that fertilizes the land.

2. Plant-based compost: After the animals are moved off the field, and wheat seeds planted, a plant-based compost is applied to the field. The compost was created in an aerated pile system [82] prior to application.

Each of these are subject to specific restrictions [223][5]:

1. Raw animal manure, if applied directly to the land, must be "incorporate into the soil not less than 120 days prior to the harvest of a product whose edible portion has direct contact with the soil surface or soil particles".
2. Plant-based compost must be "produced through a process that (i) established an initial C:N ratio of between 25:1 and 40:1; and (ii) Maintained a temperature of between 131°F and 170°F for 3 days using an in-vessel or static aerated pile system".

For example, Figure 6.28 is a MoSS model for plant-based composting activities.

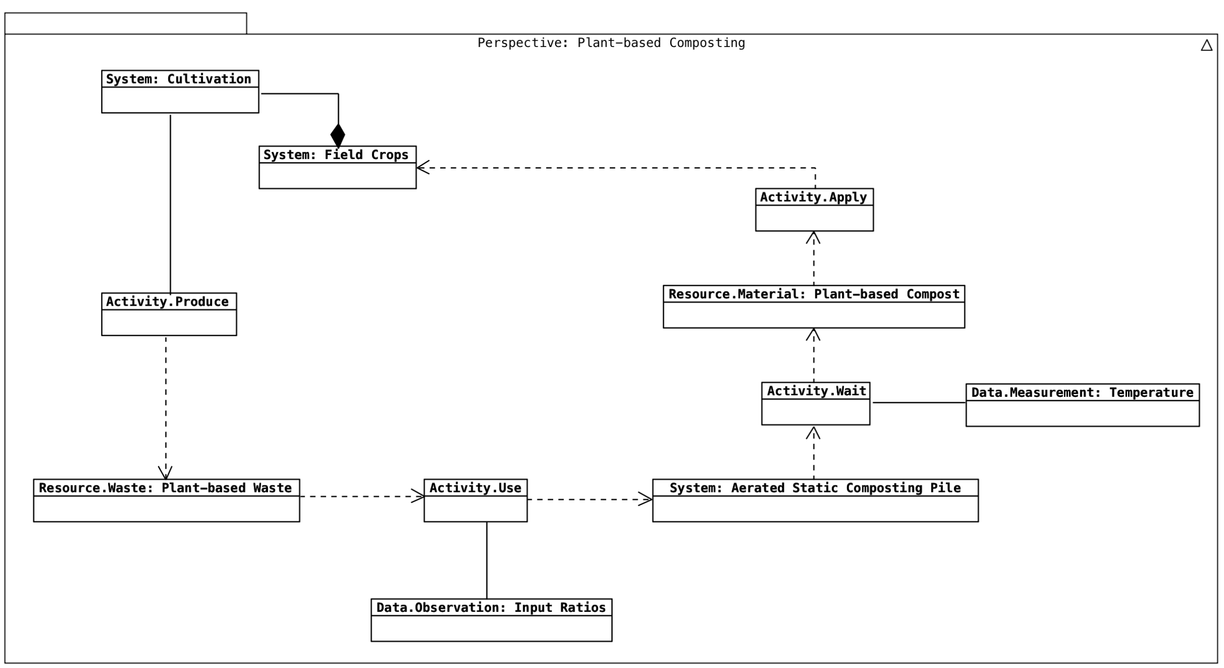


Figure 6.28: Maribel Farms: Plant-based composting, MoSS model.

[5]The restrictions listed here are only those applicable to the scenario described at Maribel Farms. There are other restrictions depending on the specifics of the manure or plant material processing and application.

This partial model can then be evaluated for compliance with the NOP using the following model checking Condition 2:

```
NOP Condition 2 - PLANT COMPOST
ACPS = system : AERATED STATIC COMPOSTING PILE
inputRatio = resource.waste-data.observation: INPUT RATIOS [value]
waitTime = ACPS-activity.wait [duration]

farm: MARIBEL = perspective.assessment/condition: PLANT COMPOST
  if  (inputRatio >= 25 && inputRation <= 40) &&
      (waitTime >= 3) &&
      (temperature >= 131 && temperature <= 170):
          farm: MARIBEL[certified.organic] = true
  else:
        farm: MARIBEL[certified.organic] = false
```

Part 3: Checking `farm/resource.inputs` for prohibited substances. A farm that intends to be certified-organic must track, at the very least, what resource inputs are applied to fields. NOP subsection §205.105 is concerned with the use of allowed substances (and the absence of prohibited substances) on farmland on which crops to be certified-organic are grown. Subsection §205.300-311 states that at least 95 percent of the inputs must be in turn certified-organic for the resulting crop to be certified-organic.

NOP subsection §205.204 requires that the seeds must also be certified-organic. A caveat is available: "Nonorganically produced, untreated seeds and planting stock may be used to produce an organic crop when an equivalent organically produced variety is not commercially available " [231]. Certifying agencies can, for example, require purchase requests or quotes from at least three suppliers showing to demonstrate that a good-faith effort to purchase organic seeds was not successful and conventional seeds must be used.

Consider again, the production of the `crop: WHEAT` in the `system: FIELD CROPS` in the `farm: MARIBEL FARMS`. Each of the activities associated with this the field crops cultivation system has an associated list of `resource.inputs`.

There are two ways in which resource inputs can be proven to be organic:

1. The resource has been externally certified-organic and has NOP labeled or listed in a public certified directory, such as the Organic Materials Review Institute (OMRI) directory. Figure 6.29 shows an example of both a label and the OMRI listing for a certified-organic pesticide.

2. All substances, ingredients, methods used to produce and handle the material can be shown to be NOP compliant: in the case of the compost produced at Maribel Farms, as described previously, the farmer would have to demonstrate NOP compliance by logging all activities and resource inputs related to the composting system.

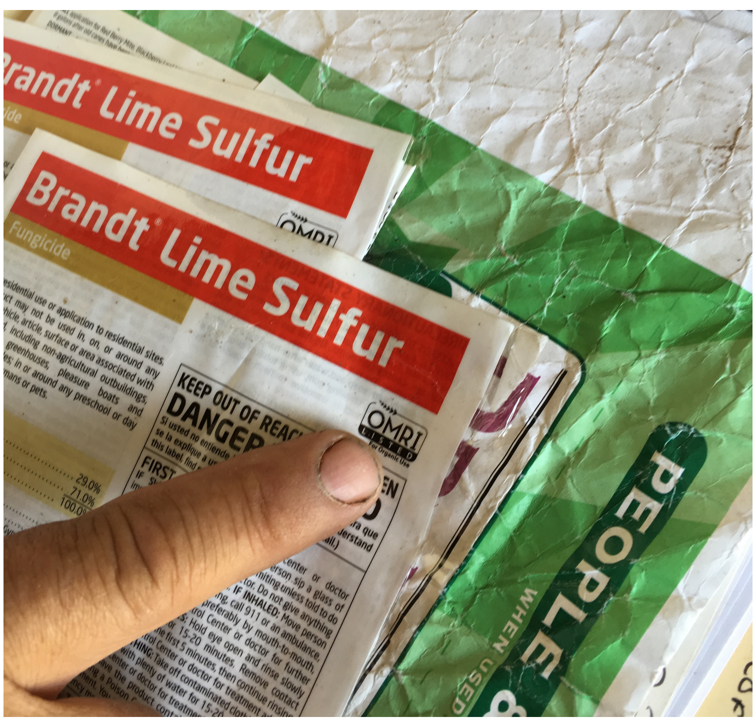


Figure 6.29: Example OMRI label of a fungicide (Photo source: Brooks Organic Orchard, a participating farm presented in Chapter 4).

The two types of `resource.inputs` of interest are: `materials` and `crop/seed`. Evidence of the resource purchase can be in the form of an image of the packaging label or an invoice. These `data` can be associated with the `resources` as shown in Figure 6.30

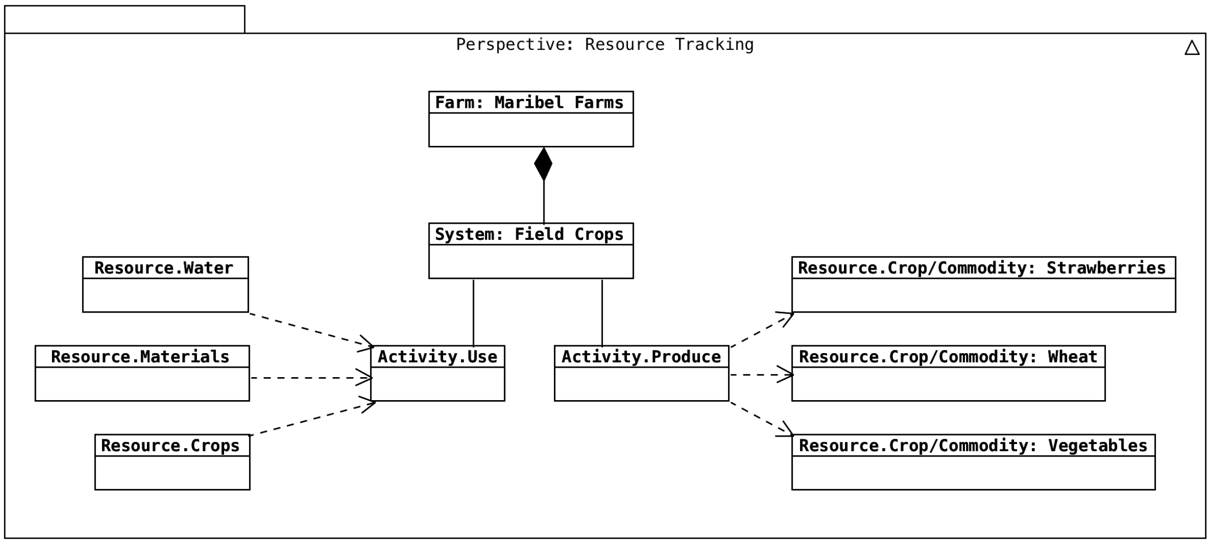


Figure 6.30: Maribel Farms: Resource inputs and crop outputs of the field crop cultivation system, MoSS model.

Figure 6.30 therefore models all `resource.inputs` to the `system: FIELD CROPS`, and the associated `data` to check for NOP compliance. This partial model can be evaluated model for compliance with the NOP using the following model checking Condition 3:

```
NOP Condition 3 - RESOURCE INPUTS
farm: MARIBEL = perspective.assessment/condition: RESOURCE INPUTS


  //Organic Materials Reveiw Institute list of approved certified-organic resources
  import omriDirectory


  cultivationSystem = scope (system: CULTIVATION)
  materialInventory = inventory (resources.materials -> cultivationSystem)
  cropInventory = inventory (resources.crop -> cultivationSystem)
  %% Continued on next page
```

```
//Check resources for prohibited substances
for (material in materialInventory):
  if (material.source in omriDirectory) || (material [certified.organic] = true):
    farm: MARIBEL[certified.organic] = true
  else:
    farm: MARIBEL[certified.organic] = false

//Check seeds for compliance
for (crop in cropInventory):
  if (crop.source in omriDirectory) || (crop [certified.organic] = true):
    farm: MARIBEL[certified.organic] = true
  elif (resource.crop-data.observation [type] == exemptionRequest):
    farm: MARIBEL[certified.organic] = flagRequest
  else:
    farm: MARIBEL[certified.organic] = false
```

Thus, the National Organic Program requirements (Table 6.9, page 221) can be represented through use of `farm/components`, `farm/activities`, and `farm/resource.inputs`, among other MoSS elements. The full NOP is a complex document with many possible interpretations, as evidenced by the breadth of certifying agencies. To port the entire standard to MoSS would likely require a dedicated effort in specifying the domain-specific elements for certified-organic agriculture, as well as specifying a complete set NOP assessment perspectives and model checking conditions.

6.5 Discussion

MoSS is three-part framework designed in response to the challenges described in Chapters 3 and 4, first presented in Chapter 5, and subsequently evaluated in this chapter. It consists of an abstract model, a body of domain-specific elements, and perspectives. The MoSS framework is visualized in Figure 6.31.

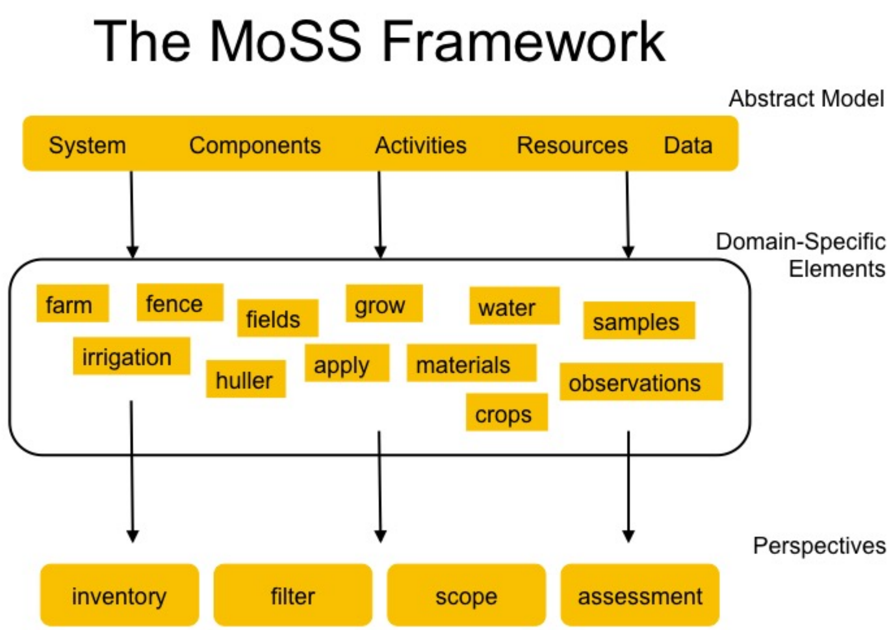


Figure 6.31: The MoSS framework.

The core abstract model decomposes the world into space, time, and information. Similarly, the perspectives are relatively domain-agnostic: filters, scopes, inventories, language for assessments, and the use of conditions and loops are not unique to agriculture. However, both the abstract model and the perspectives are crucial to the success and functioning of the MoSS modeling process. The domain-specific elements are where the influence of the farm data and findings described in Chapter 4 is more apparent. It was in the laying out of the domain-specific elements that the threat of overspecialization loomed. It is during the articulation of these elements that engaging in both theoretical sensitivity and having a broad set of resources was most critical. The three parts of MoSS can be summarized as follows:

1. The abstract model provides the core foundation to capture basic system attributes.
2. The more nebulous set of domain-specific elements are designed to capture unique properties of sustainable agricultural systems.
3. The MoSS perspectives allow us to view a specific system model through various lenses.

In this chapter, I evaluate MoSS with respect to eight modeling scenarios across three hypothetical farms. Each of these scenarios was intended to require the performance of various types of modeling activities that were found (see Chapter 4) to be common in a set of small- to medium-scale sustainable agriculture. In this section, I first describe a set of threats to the validity of the scenario-based evaluation, and then discuss how MoSS did (and did not) meet the design requirements laid out in Chapter 5, and what forms of environmental assessment are indeed supported.

6.5.1 Threats to Validity

During the design of MoSS, five Farm Personas were developed, primarily based on the 16 farms that participated in the study presented in Chapter 4. In the evaluation activities of this chapter, three of these five personas were used, and detailed scenarios were developed. While scenario-based evaluation proved to be a useful tool for exploring the expressiveness of MoSS, there are three main threats to the validity of this evaluation:

1. Potential for overspecialization: Both the design and evaluation of MoSS relied on the same initial set of personas. There is a danger that MoSS is too specific to these representation of Californian sustainable agriculture.

2. Lack of expert vetting: the personas and scenarios were not explicitly vetted by experts in sustainable agriculture.

3. Potential mismatch with conceptual models of farmers: while I did attempt to conduct a user-based evaluation (see Chapter 5, Section 5.1, Iteration 2), there was no further farmer consultation in the design MoSS.

To combat these threats, the personas were refined and scenarios created using farm descriptions from agriculture research literature, materials produced for beginning farmers, and issues presented in farmer-oriented media. Each of the scenarios were designed to require new dimensions of the Farm Personas that were not explicitly articulated during the design activities. In particular, the level of detail in scenarios required the specification of the details of how, say, environmental stewardship was actually practiced at Blackbird Gardens, or how organic certification could be conducted at Maribel Farms. These details were based on reports of real world challenges. For example, in the Farmer-to-Farmer podcast [49], Chris Blanchard interviews farmers about their farming philosophies and the pragmatics of farming. This type of engagement allowed for reduced reliance on the same details of the Farm Personas used in the design work.

Further, by consulting publicly available educational courses on topics such as Community Supported Agriculture [41], I adopted the role of a beginner farmer to steep myself in the challenges of farming in the 21st century. This allowed for the consideration of expert advice on specific agricultural practices. While not a substitute for expert vetting of scenarios, it did provide perspective and guided the the level of detail I was comfortable describing in the scenarios as a non-domain-expert.

Finally, through attendance at sustainable agriculture related activities and continued engagement with local agricultural communities, the challenges, restrictions, and needs of sustainability-oriented farmers were consistently reinforced. Speaking with farmers during attempted user-based evaluations also allowed for informal feedback regarding the construction of MoSS.

Even with the attempts to combat the threat of overspecialization, the version of MoSS presented closely reflects a spectrum of sustainable agriculture in California as explored in this dissertation.

6.5.2 Meeting the Design Requirements

First, let us consider the coverage of the each MoSS element by the scenarios presented in this chapter, as shown in Table 6.10. This table demonstrates that the persona-scenario sets used in this evaluation adequately cover the MoSS framework thereby allowing for an appropriate evaluation of MoSS to take place. Each of these elements, with the exception of `resource.money` and `resource.energy` were used in at least one scenario (more on this later). MoSS perspectives were used to enable partial model creation, and MoSS modeling heuristics were articulated to guide modeling activities, as demonstrated in each of the scenarios.

Coverage of MoSS Elements	Farm Persona		
Component	**Blackbird Gardens**	**Luna Orchard**	**Maribel Farms**
component - high level	1.1	2.1	3.1
system	1.1	2.1, 2.3	3.1, 3.2
field	1.1, 1.2	2.1	
structure	1.1	2.3	
boundary			3.2
conveyance		2.3	
blackBox			3.1
component - unit level		2.1, 2.2	
layer		2.1	
Activity			
create | produce | get | collect	1.2	2.2	3.2
destroy | consume | give | delete	1.2		3.2
update | move | store			3.2
block	1.2	2.2	
Resource			
water		2.3	3.2
materials	1.2, 1.3		3.2
crop	1.2	2.2	3.2
waste			3.2
money			
energy			
Data			
observation	1.3	2.2	3.2
measurement	1.3	2.2	3.2
sample	1.3	2.2	
test		2.2, 2.3	
Scenario	1.1 The structure of a farm 1.2 Crop rotations 1.3 Environmental stewardship	2.1 Multilayer Layouts 2.2 Diagnosing a tree 2.3 Tracking water	3.1 System of systems 3.2 Organic certification

Table 6.10: Scenario coverage of MoSS elements.

In Section 4.3 of Chapter 4, I describe the information management practices of small- to medium-scale farmers in California that I uncovered as a result of the qualitative study conducted. In particular, I detail what types of farm data are collected, what data collection techniques are commonly used, and how these data are modeled. Table 6.11 maps which scenarios express each data type and/or collection technique.

Farm Data Coverage	Farm Persona		
Model environmental data	**Blackbird Gardens**	**Luna Orchard**	**Maribel Farms**
weather			
land	1.1, 1.2, 1.3	2.1, 2.2	3.2
weeds and pests	1.3	2.2	
wildlife	1.3		
Model resource data			
water flows		2.3	
material flows	1.2, 1.3		3.2
energy, waste, or money			
Model operational data			
Data collection techniques			
observations	1.3	2.2	3.2
sampling	1.3	2.2	
sensors	1.3		
Scenario	1.1 The structure of a farm 1.2 Crop rotations 1.3 Environmental stewardship	2.1 Multilayer Layouts 2.2 Diagnosing a tree 2.3 Tracking water	3.1 System of systems 3.2 Organic certification

Table 6.11: MoSS coverage of farm data in small-to medium-scale sustainable agricultural systems.

As can be seen in Table 6.11, there are three categories of of farm data that have *not* been modeled using MoSS:

1. *Data regarding weather:* Farmers both consult externally reported weather reports, as well collect their own weather-related data (e.g., rainfall and temperature) to guide their agricultural activities. Weather data is also primarily used in day-to-day decision making, as opposed to for environmental assessment, as is the focus of MoSS at this stage.

2. *Data regarding energy and money:* Systems concerned with money and energy are complex systems in and of themselves. Modeling these would introduce an addition level of complexity to MoSS that requires extensive domain knowledge. As these were not explored in detail during either the on-farm interviews (Chapter 4) or the formal modeling investigation (Chapter 3), they were deemed outside the scope of this first version of MoSS.

3. *Operational data:* Data regarding day-to-day farm management was also outside of the scope of this version of MoSS, primarily due to a lack of access to real operational data on the farms discussed in Chapter 4.

There are many other data categories, in particular those related to livestock, were not even considered in the design of MoSS due to dissertation scoping constraints. These are not reflected in the Table 6.11 as no domain-specific elements were created for them, but it is important to note that these missing data represent gaps in the expressive capacity of MoSS.

Further, while much attention was given to data collected through observation and sampling, data collected via sensors was also *not explicitly* modeled using MoSS.

4. *Sensors:* In Scenario 1.3, regarding environmental stewardship at Blackbird Gardens, a sensor is used to measure the number of bats visiting at particular bat box to monitor actual use. This is a fairly basic example, and sensing technologies range in sophistication. To truly evaluate whether or not MoSS is capable of expressing data collected through sensors, scenarios would need to be created looking explicitly how such data would be collected and integrated into a MoSS model. Such as a scenario could, for example, involve the creation of MoSS model to explore adaptive/responsive irrigation techniques that utilize moisture sensors (to detect water retention by soil post-irrigation or to monitor how far below surface the water seeps).

Prior to introducing the MoSS framework, I defined six characteristics that a modeling language for sustainable agriculture should exhibit: abstraction, composition, modularity, granularity, and adaptability. These characteristics were first identified in Section 7.2 of Chapter 3, as guidelines for design work, given the drawbacks of life cycle assessment for sustainable agriculture. These characteristics were reinforced by the lessons learned regarding the information management practices of farmers (Section 4.4.3, Chapter 4), and finally re-articulated as design requirements for MoSS in Section 5.2 of Chapter 5. I argue that a modeling language that has these characteristics would be better suited to modeling sustainable agricultural systems. Therefore, I evaluate MoSS with respect to each of these characteristics.

6.5.2.1 Abstraction

In order to uphold principles of abstraction (as discussed in Chapter 2, Section 2.2) a modeling language must support the modeling of complex systems, support the creation of hierarchic structures, and encourage the separation of concerns. Please note, I focus on the discussion of representing complex systems and the separation of concerns in this section, but hierarchic structures are discussed in the later section on *Composition*.

Each of the agricultural systems represented in these Farm Personas exhibit various forms of complexity. While Luna Orchard is a spatially complex system, Blackbird Gardens, with its intricate crop rotations and interdependencies between activities, is a temporally complex system. The crop diversity at Blackbird Gardens also makes it a more heterogenous system, however, the product and process complexity (and therefore heterogeneity) is greater at Maribel Farms.

MoSS currently handles model and system complexity in two ways:

1. *Use of Perspectives*: Currently, MoSS provides `perspective` elements that allow for the selective display of a greater system model. These have been used in many of the scenarios presented in this chapter to hypothetically filter a full system model to only show a partial model. For example, the MoSS model in Figure 6.21 (page 209) represents data related to tree health and problem areas in a 1-acre subsection of a single field (Field Mandarin) at Luna Orchards.

2. *Separation of concerns:* MoSS modeling heuristics 8 and 9, in Section 5.7, Chapter 5, recommend two ways in which models should be created to enforce a separation of concerns. MoSS heuristic 8 suggests the separation of spatial and temporal dimensions through the use of `components` and `activities` to differentiate between structural and behavioral properties of a system.

   MoSS heuristic 9 suggests the separation of `data` and all other system elements to both enable data reuse, but also to allow for the manipulation of data without affecting either the spatial or temporal system representations.

However, it is not clear that MoSS models will scale with any greater system complexity. Handling greater model complexity is an open challenge with the current version of MoSS. It will be important to engage in real world modeling with MoSS to be able to both test for scalability and subsequently refine the design to cope with increasing model complexity.

Nevertheless, the core strength of MoSS lies in its ability to represent a diversity of agricultural systems using the level of abstraction that is most appropriate for the modeling goal at hand.

6.5.2.2 Granularity

MoSS enables the representation of a system at varying levels of granularity. There are no required elements of a MoSS model, instead, elements are chose to represent areas of interest in a system.

The core model provides basic elements, that can be used to create abstract high-level system models, while the domain-specific elements allow for more nuanced modeling when needed. For instance, each of the first scenarios of each of the Farm Personas, result in a MoSS system model with varying levels of detail:

1. *Unit level:* At Luna Orchard (Scenario 2.1, page 202), the system model specifies the layout down to the tree level within each field.

2. *Field level:* Blackbird Gardens (Scenario 1.1, page 188) contains a system model that represents the fields and structures within the farm, without dropping down to the row level, or specifying where each head of lettuce is placed.

3. *System level:* While at Maribel Farms (Scenario 3.1, page 217), the system model simply represents each of the cultivation systems as subsystems through a system-of-systems style model.

In each of these cases, the level of detail used in the model is chosen based on the modeling requirements of such a farming system. Specifying new domain-specific elements to capture system attributes that this version of MoSS was not designed for, can be as simple as extending an existing element and specifying it to support modeling of the system attribute of interest.

6.5.2.3 Composition

MoSS enables collective representation of system attributes. The abstract elements `system`, `component`, `activities`, `resources` and `data` represent the basic units of representation. MoSS then provides mechanisms to create hierarchic structures, group related elements based on some attribute, connect elements to each other to form subsystems, and encourages encapsulation.

1. *Hierarchies:* MoSS inherently supports the creation of hierarchic structures by adopting Object Oriented Modeling concepts such as inheritance and aggregation/composition. This not only allows for the creation of element families with shared attributes, but

also enables creation of whole/part relationships. These relationships are described in Table 5.2 of Chapter 5.

2. *Groups of elements:* In the spatial dimension, `components` can be grouped into `layers`. This enables for the collective representation of, for example, a layer of crops (as shown in both Luna Orchard's Scenario 2.1). This allows for data to be associated at multiple levels within the same model. In the MoSS model relating to tree health issues, Figure 6.21 data are associated both with individual trees, as well as with an entire field. In this particular case, data are also nested to create an *area of interest* that contains all the data related to a particular investigation.

   `activities` can also be grouped into `blocks` to allow for the representation of interdependent activities. For example, in Scenario 1.2, `blocks` are used to represent rounds of planting crops at Blackbird Gardens.

3. *Subsystems:* As exemplified in the system-of-systems model shown in Maribel Farms' Scenario 3.1, a system can be composed of many other systems. While there were no examples of the details of these subsystems at Maribel Farms, other scenarios provide insight into what they may look like. The water infrastructure model shown in Scenario 2.3 for Luna Orchard is a subsystem model focused entirely on modeling aspects of an system related to farm irrigation.

4. *Encapsulation:* The use of encapsulation is encouraged (MoSS Heuristic 6) and supported through the `layer, block, and blackBox` elements. Each of the examples discussed in this section are also instances in which model elements were encapsulated in order to provide a higher level model.

6.5.2.4 Modularity

While MoSS provides support for creation of model subcomponents, there are no *explicit* interfaces that indicate how groups of MoSS elements can be connected as modules. An open challenge involves true modularity in MoSS models.

Currently, the relationships specified for use between elements within a model would be used among elements and groups of elements across models. For instance, the `inputs` and `outputs` of `activities` can be considered as pseudo-interfaces as the input and output resources can be used to connect one system to the other.

Consider this example[6]: Wild Valley Vineyard produces grapes for wine. As part of the winemaking process, *grape pomace* — solid grape waste produced as a result of pressing grapes for wine — is produced. Grape pomace can be used as both fertilizer and an animal feed supplement. Assume Wild Valley Vineyard trades their Grape Pomace to the farmers at Sundance Ranch, where they use it to feed their livestock. Here, the output of one system (Wild Valley Vineyard) is an input to another (Sundance Ranch). One could theoretically just model Wild Valley Vineyard as the source attribute of an input resource to Sundance ranch as follows:

```
resource.waste [type: GRAPE POMACE, source: WILD VALLEY VINEYARD] -> farm: SUNDANCE RANCH
```

However, an opportunity is missed to enable a flow of information regarding the provenance of the grape pomace. If one system is certified organic, how may this information be carried over to the next model?

For MoSS to support the creation modular models, the next version of MoSS will require explicit consideration of element interfaces.

[6]based on two Farm Personas that were not used in this evaluation, but that were part of the original set of Farm Personas as mentioned in Table 6.1

6.5.2.5 Adaptability

MoSS does not sufficiently capture changes in a system: it still relies on static representation of dynamic systems. The core weakness of the current version of MoSS involves the representation of time.

Once a MoSS model is created, any changes in the real world system would require that one either re-models the changes in the system, or updates relevant model attributes. However, there is no change tracking available to indicate which elements have been changed and when. MoSS models therefore suffer from the same issue that LCA models do (as discussed in Chapter 3): they do not explicitly capture information regarding how both the model elements and the system in the real world change over time.

The closest MoSS comes to creating models that capture changes is through the combined use `activities` and snapshot models. This is best exemplified through the combination of the crop layout and crop rotation MoSS models shown in Figure 6.8(page 192) and 6.10(page 195) respectively.

The crop layout model indicates which crops are planted where, and when. It provides a snapshot of the system at a specific moment in time. The crop rotation model tells us how and when the crops are going to be planted. It provides perspective on the changes that the system will undergo. This means that a crop layout can be inferred based on the multi-year crop rotation plan (see Figure 6.9). Further, the process described here still does not track model changes and it would be unclear when the model was updated.

MoSS models are therefore not inherently adaptable, and the representation of change, while somewhat doable, is still a complicated and messy process.

6.5.3 MoSS for Environmental Assessment

Let us now turn to the intended use of MoSS models, as described in the findings of the qualitative study of Chapter 4 (Section 4.3). The goal of this section is to evaluate how well MoSS supports environmental assessments of small- to medium-scale sustainability-oriented farms.

MoSS was not designed to support a *specific* environmental assessment technique. Instead, it was designed to support a range of assessments, as conducted by the 16 Californian farmers interviewed, and as recommended in agricultural literature. Given this, most of the scenarios presented in this chapter were concerned with informal environmental assessments as opposed to formal techniques such as Life Cycle Assessment. In this section, I describe each of the categories of assessment supported by MoSS, as evidenced through the scenario-based evaluation.

6.5.3.1 Certification

Scenario 3.2, concerning Maribel Farms was the only scenario to demonstrate how MoSS may be used to engage in record keeping and assessment with respect to an external certification. The primary focus of this scenario was on modeling Maribel Farms in order to check for compliance with National Organic Program for the field crops to be certified-organic. With the rise of organic agricultural certifications, this scenario is one of the most applicable real world uses of MoSS.

To assess whether or not a farm is NOP compliant and therefore eligible certified-organic, the following steps would need to be conducted:

1. Specify all subparts of the NOP regulation applicable to the system of interest (for instance, as excerpted in Table 6.9) using MoSS model checking conditions (as exemplified in Scenario 3.2).

2. Create MoSS model(s) representing all relevant aspects of the agricultural system to be certified.

3. Check the farm's MoSS model(s) agains the NOP model checking conditions for compliance.

However, this only allows for a one-time assessment of a detailed system model. In order to continuously maintain up-to-date system models that, for example, flag the modeler when a system falls out of compliance, the current method requires additional capacities:

1. MoSS models should track changes in order to allow for a) system change history to be available (as is needed by NOP).

2. A mechanism to recheck the model agains the NOP model checking conditions on-change.

3. A mechanism to ensure that the NOP model checking conditions are also up-to date as the program itself gets updated.

While these are not insurmountable challenges, for MoSS to be usable as for compliance assessment, MoSS would need to be refined to support these additional capacities..

6.5.3.2 Regulation or Incentive Program

Two scenarios presented in this chapter considered the use of MoSS to participate in U.S government run agricultural programs. In Scenario 1.3, the farmers at Blackbird Gardens engage in environmental stewardship activities, with the intent of eventually participating in the EQIP program. Scenario 2.3, regarding the modeling of water infrastructure, mostly focuses on demonstrating how MoSS may be used to model water-related data in a farm. However, some of these data are also used for participation in the Irrigated Lands Regulatory Program for reporting water emissions.

In each case, the scenario did not explicitly demonstrate how MoSS would directly connect to the regulatory or incentive program. Instead, the scenario focuses on structuring farm data first to support internal assessments, with a possible second use being for program participation. This was in keeping with the findings of Chapter 4, where I describe the multiple purposes of farm records. I argue that by creating models that allow farmers to answer their own questions first, and report performance second, we can actually support on-farm environmentally-oriented activities, as opposed to simply creating a mechanism for single-use regulatory reporting.

6.5.3.3 Internal Assessment

Most of the scenarios further focused on supporting internal environmental assessment activities and the practice of sustainable agriculture. Four of the scenarios presented in this chapter — Blackbird Gardens' Scenarios 1.2 and 1.3, and Luna Orchard's Scenarios 2.2 and 2.3 — focused on modeling the farming system and structuring farm data to support internal assessments.

While Scenario 1.2 focused on supporting the sustainable agricultural practice of crop rotations, Scenario 1.3 more directly modeled disparate farm data regarding the environmental stewardship activities at Blackbird Gardens. Luna Orchards' Scenario 2.2 similarly knit together typically disconnected farm data, to provide perspective on tree health issues on the farm. Current modeling tools, farm management software, and environmental assessment techniques do *not* support the creation of such assessment perspectives. These scenarios demonstrate a core strength of MoSS: it enables the creation of new perspectives to allow for assessment of the environmental performance of an agricultural system. The modeler can effectively view any aspect of the system model their desire to engage in their own form of assessment.

6.5.4 Moving Forward

In each of the scenarios presented in this chapter, MoSS captures a blend of qualitative and quantitative data, collected using varying techniques by different data stakeholders, and that could be used to answer a variety of questions regarding the environmental performance of the farm, in a single coherent model. To this end, MoSS met the design goals articulated over the last few chapters.

While there are many issues to be resolved — from data interoperability and handling potential issues due to increasing model complexity, to more appropriately management of change and the representation of time — the scenarios presented in this chapter demonstrate the potential the MoSS framework, and the types of activities that can be supported in sustainable agriculture through grounded farm-centered design.

At the heart of the scenario-based evaluation presented in this chapter lies the question: does MoSS effectively model farms as complex adaptive systems? In conclude with mixed results: this version of MoSS performs well with respect to capturing complexity, there there exist gaps in being able to effectively capture changes, and the ability to capture context remains only partially explored. For MoSS to meet the broader goal of *any* modeling sustainable agricultural system, the future of MoSS needs to involve: MoSS refinement activities; re-engaging with small- to medium- scale farmers, to further specify MoSS elements and testing of heuristics; evaluation of MoSS in practice; and the design of modeling tool for use by farmers and other farm data stakeholders.

Chapter 7

Reflections

> *"[C]onsider the numbers involved. Some small vegetable farms may grow thirty-five or more different crops. And to spread out the offerings, they may sow four or five cultivars of some of them. Successional harvests require numerous planting dates. Those dates are determined by keeping careful notes during previous years. In total, that amounts to hundreds of varied and possibly unique decisions about crop rotations, soil types, specific planting and harvest dates, labour requirements, storage and handling, and other factors. [...] So let's start at the beginning of your year."*
>
> — Eliot Coleman, Letters to a Young Farmer [201].

In an age of ever growing complexity, we must both find ways to simplify our systems and to understand the intricacies of our web of systems in more nuanced ways. As information designers, it is within our purview to engage in the design of how we model complex adaptive systems to meet human, social, economic, and environmental goals. As researchers, it our privilege to be able to take a step back, and start with more fundamental questions: what is information, why do we model, what is possible?

In this dissertation, I presented the MoSS framework for Modeling Sustainable Systems. It is but a single step toward grounded information design for sustainable agriculture. I have argued that a coherent and flexible mechanism by which we can model systems, such as those found in sustainable agriculture, is for example, required to:

- effectively design information management tools;
- create low-effort assessment techniques and regulations; or
- optimize the performance of our systems with respect to sensitive environmental contexts and the myriad of environmental interactions.

MoSS was born of a marriage between formal modeling techniques and both farm- and human-centered design. In this chapter, I tie together the work presented in each of the previous chapters to 1) provide an overview of my contributions to modeling in sustainable agriculture (Section 7.1), and 2) engage in a broader discussion of the implications of the work I present in this dissertation (Section 7.2).

7.1 Summary of Contributions

Modeling in Agriculture: The work presented in this dissertation began with an investigation of how Life Cycle Assessment (LCA) techniques are used to model agricultural systems in order to explore their environmental impacts. A review of modeling practices in the LCA literature focused on agriculture resulted in the following seven observations regarding modeling trends:

1. The scope of analysis is typically cradle-to-gate.
2. The unit of analysis is typically land use or commodity quantity.

3. Granularity of LCA models is fixed at the unit-level.
4. Comparisons are made across agricultural systems with different agricultural practices.
5. Comparisons are made across agricultural systems in different geographic regions.
6. Comparisons are made across entire production systems in different geographic regions.
7. Models across entire sectors in agriculture are often compared and sometimes connected.

Following this assessment, I envisioned a set of scenarios that small-scale sustainable agricultural systems may face where the LCA modeling process may be used. Through this scenario-based analysis, a set of issues in using LCA methods, tools, and data structures for sustainable agriculture became apparent. These issues were synthesized as three essential difficulties – akin to those found in software engineering [31]: capturing complexity, changeability, and the context of agricultural systems. These challenges result in a mismatch between the underlying LCA modeling language, workflows, and tools with the modeling requirements of small-to medium scale sustainable agricultural systems.

I argued that these difficulties arise because agricultural systems are, in fact, complex adaptive systems, and the LCA modeling process was not explicitly designed to capture the characteristics of such systems.

In software modeling, the Object Oriented Modeling (OOM) approach came about as a response to analogous difficulties inherent in different complex adaptive system specifically, software systems. Therefore, extending this work, by taking an OOM approach to modeling the environmental impact of agricultural systems, appeared reasonable.

I proposed that a new modeling language for the domain of sustainable agriculture was required and described five requirements for such a language to effectively overcome these modeling challenges:

1. The ability to create abstract models grounded in system-level data.
2. The ability to compose subsystems and decompose systems through the use of objects.
3. The ability to create modular and interconnectable system models.
4. The ability to represent systems at varying levels of granularity.
5. The ability to capture change in systems.

While such a language would not be a silver bullet, it would be a valuable step toward create coherent mechanisms to capture complex and adaptive agricultural systems.

Exploring Sustainable Agriculture: Next, I took to a grounded exploration of information management and environmental assessment in sustainable agriculture. I conducted a qualitative field study, visiting 16 farms in Spring 2016, with the goal to understand how small- to medium-scale sustainable farmers model their systems in practice. The study was guided by the Grounded Theory Method, which is typically used to "develop an inductively derived grounded theory about a phenomenon" [53].

This study explored: the structure of diverse farming systems; variances in farm data and data collection practices; the policy and environmental context of sustainable agriculture; and farmer experiences in creating farm-level models.

I found that the information management challenges faced by farmers involved the capture of complexity, changeability, and context of their farms. Further, restrictions on farm-data were imposed by: environmental policy and certifications; the human and social context; and the ever-present mismatch between systems, models, and tools.

The findings of this study were distilled as seven lessons for design in sustainable agriculture:

1. There is a need to standardize data structures that model disparate types of farm data.

2. There is a need for a consistent modeling workflow that is sensitive to the varied mediums of technology used by farmers.

3. There is a need for models that can represent varying levels of abstraction, formality, and granularity.

4. There is a reusability gap between data collecting for each of the models that are created.

5. There is a lack of change tracking across models representing farms as the farms change.

6. There is a gap between data collection goals triggers and the eventual use of farm data and models.

7. There is a need for increased support for coordination and collaboration on farms.

However, lessons alone do not a grounded theory make. The findings of this study, in conjunction with the findings of the LCA analysis, however, do provide a grounded basis to engage in design work for sustainable agriculture.

Introducing MoSS: Taking into consideration the findings presented in Chapters 3 and 4, I set up a design prompt, and re-articulated the requirements for modeling the environmental impact of small- to medium-scale sustainability-oriented farms.

The design of MoSS involved the adaptation of the Grounded Theory Method (GTM) for the design of a modeling framework for sustainable agriculture. In this dissertation, I also introduced three new design methods:

1. *GTM for model design:* By connecting the preliminary results of GTM activities (codes and categories) to seed elements of MoSS, I demonstrated how GTM may be used for model design.

2. *System Personas:* I instantiated the concept of a System Persona through a set of Farm Personas, presented as tools for design. The idea of personifying a farm may be abstracted further to the personification of an entire organization to enable design for organizations (where, humans are still recognized as actors, but intrinsically a part of the greater system).

3. *Paper prototypes for evaluating conceptual models:* While I was unable to conduct a full evaluation due to recruitment issues, I found the development and use of the paper prototypes for evaluating a conceptual model (as opposed to, for example, software interfaces) to be a valuable refinement activity.

It is through this iterative design process that I arrived at MoSS, a framework to enable the Modeling of Sustainable Systems. In Chapter 6, I demonstrated MoSS's capability to meet these claims through a scenario-based evaluation. MoSS, as instantiated in this dissertation for the domain of Sustainable Agriculture, possesses the following capabilities:

1. Represent heterogeneous farm data, both qualitative and quantitative;

2. Represent spatial complexity, including heterogeneous components, nested subsystems, and at varying levels of granularity;

3. Represent feedback and interdependence among farm elements, including farm context;

4. Create models to meet various modeling goals of farm actors and data stakeholders, including environmental assessments; and

5. Generally provided consistent mechanism by which small- to medium- scale sustainable agricultural systems can be represented.

Open issues in the version of MoSS presented in this dissertation include:

1. Lack of representation of weather, energy, money, livestock, and operational data, and consideration of sensor-collected data;
2. Handling of increasing model and system complexity;
3. Connecting modular system models to allow for tracking and exchange of information and resource across farms;
4. Representation of temporal complexity, including tracking model change, and changing properties of farm; and
5. Lack of explicit support for formal environmental assessments.

These issues primarily reflect the limited scope of the dissertation, and may be addressed through future explorations and refinement. The version of MoSS presented in this dissertation is, essentially, MoSS Version 1.0, which is to say, the process of taking MoSS from concept to practice will involve further model refinement, iterations to include broader sets of design inputs, and a more formal specification underlying the language itself.

In this dissertation, I sought to understand the means by which we can assess the environmental performance of agricultural system and to subsequently design and develop solutions for sustainable agriculture. By supporting small- to medium-scale sustainable farmers, I aim to support the global transition to sustainable food systems. Given interest in building, maintaining, and improving the environmental performance of our agricultural systems, there is an urgent need to further explore the landscape of environmental assessment and agricultural modeling, as well as opportunities for collaborative software design.

7.2 Broader Implications

In this section, I consider the broader implications of this dissertation in three parts: design for sustainable agriculture, opportunities for software engineering, and the future of MoSS.

7.2.1 Design for Sustainable Agriculture

Agricultural systems are complex adaptive systems that span across geographies, economies, societies, and other boundaries. Designing technologies in support of sustainable agriculture, therefore, requires engagement across institutions: it requires collaboration between software designers, policy makers, agricultural extension agents, agronomists, and farmers. This makes the challenge of modeling sustainable agriculture and the design of appropriate technologies a deeply interdisciplinary one. We will encounter three[1] immediate challenges as we continue to design for sustainable agriculture:

1. Contextual Design: The first challenge is regarding the human and policy context of agriculture. In Chapter 4, I had described three types of restrictions faced by small farmers in California: those as a result of the policy context, the human and social context, and those resulting from a mismatch between systems, models, and tools.

As a software community, we have developed techniques to enable exploration of system-tool and human-tool mismatches. In that sense we can design to resolve this restriction somewhat amicably. However, we cannot escape restrictions placed due to policy, human, and the social context. Instead we will have to engage with these restrictions in conjunction with farmers, regulators, domain-experts and other farm data stakeholders.

[1]Indeed there are many more challenges, but the following are the most relevant to the design of technology, as well the most urgent given the changing landscape of both agriculture and technology.

2. Heterogeneous Data: The second challenge involves the consideration of heterogenous data and the implications of modeling these data. As Farmer Gary and his daughter Gina, of Glass Organic Orchards (participating farm, Chapter 4), were describing their different approaches to sampling tree productivity and the factors that affect their data collection practices, he joked: *"Where does attitude go in the database?"*

It was an important reminder that data, regardless of how rigorously it may be vetted or carefully collected, is not immune to the vagaries of life. Even when data is collected through a full automated sensor, data is still subject to human and environmental influence, among others. As more data is collected on farms for different reasons, identifying appropriate mechanisms to ensure data quality, interoperability, and longevity, will be essential. In that sense, my work with the MoSS framework was an attempt at addressing the oncoming challenge regarding the management of heterogenous data on farms.

Data is also a sensitive topic on any farm. Whether in the context of the privacy concerns when pushing data related to proprietary practices to the cloud, or issues regarding data ownership when third party tools and equipment are used for collection. Being cognizant of the complexities of farm data extend far beyond simply structuring open data.

3. The Goldilocks' Challenge: The third challenge more broadly relates to the design of appropriate tools that support varying levels of abstraction, integrate with information management practices in sustainable agriculture, and scaffolding associated environmental assessment techniques.

For instance, in my future work, I intend to design modeling tools that enable farmers to use MoSS to model their farms and subsequently assess the environmental impacts of their systems and practices. To do this, I will have to take into account the seven lessons for design described in Chapter 4, ranging from: allowing for varying mediums of technology, supporting varied modeling requirements, and enabling coordination and collaboration among data stakeholders. This will require designing a tool that is *just right* for the intended user through identifying ways in which the human-computer interaction results in a user-friendly and useful experience.

Negotiating between varying goals and the tradeoffs that exist in interface design will be crucial to any successful adoption of the MoSS framework. It requires addressing the Goldilocks challenges (first introduced in Chapter 5) at the heart of design for sustainable agriculture.

7.2.2 Opportunities in Software Engineering

Software enables us to abstractly represent complex systems in order to then efficiently and effectively access information about them [116]. In this dissertation, I focused on the application of software modeling techniques to first teasing apart difficulties inherent in modeling sustainable agriculture, and subsequently designing a modeling language to address those difficulties.

Moving forward, additional opportunities in applied software engineering research in the domain of agriculture may emerge. For instance, work on configuration management techniques, model checking methods, architecture of software modules, and the infrastructure that allows for the sharing of software libraries, may be brought to bear on the modeling challenges described in this dissertation. Some potential avenues include:

1. Providing a historical perspective on agricultural systems as they are changed and naturally evolve through the use of configuration management.
2. Enabling model reusability through appropriate representation of subsystems and creation of databases that enable the sharing of objects, templates, and models.
3. Enabling the design of more sustainable systems through prescriptive modeling.

4. Improving the environmental performance of agricultural system, whilst being sensitive to the economic and social issues at play, through the use of optimization techniques.

5. Improve the quality of models produced by checking models for consistency, completeness, and correctness through validation and verification techniques.

7.2.3 The Future of MoSS

In early 2017, I co-organized a workshop on "Designing Sustainable Food Systems" at CHI. We wrote: "From spear to drone, humans have had a long history of designing technologies to address complexities inherent in the food system, and to improve our ability to produce and consume effectively and efficiently" [181]. Around the time that we put forward this workshop proposal, I was still conducting the evaluation of MoSS, and considering what next steps I wanted to take with my work. However, this idea has been at the heart of much of the research that I have engaged in over the course of my dissertation research.

The question central to my future research remains; *what can and should we design in support of sustainable food systems?* I will briefly describe three activities as part of my future work to support modeling in sustainable agriculture.

1. MoSS Refinement: The first step involves the refinement of the MoSS framework as it has been presented in this dissertation. This would require working with farmers and other data stakeholders to evaluate the first version of MoSS, and subsequently modify MoSS to enable farmer interaction with the language. This would likely be through a series of longer on-farm studies involving observation of farm data and records in use and modeling activities akin to those presented in the attempted paper-prototype-based preliminary evaluation of MoSS in Chapter 5.

2. Participatory Design: Re-engaging with small- to medium- scale farmers as research partners will be crucial to the subsequent design of any tools to allow farmers to use MoSS as part of their information management practice. This farm- and farmer-centered approach would ideally result in the design of a modeling tool, to enable a farmer to, for example: create a model of their farm, capture farm data on an on-going basis, and use the MoSS-based models for day-to-day decision-making and environmental assessments. Ideally, I would like to work with both certification and regulatory partners to enable, for example, the organic certification of an agricultural system through the same system.

3. Tool Building: Finally, I would like to develop tools for use by farmers and other farm data stakeholders based on both the conclusions of this dissertation, the capacities afforded by the MoSS framework, and given the future activities described here.

7.2.4 Conclusion

There is significant potential for design for sustainable agriculture and engagement in issues regarding environmental sustainability through applied software engineering. Through this dissertation, I aimed to demonstrate ways in which we can address some of the core information management challenges faced by small- to medium-scale farmers and address the essential difficulties faced in modeling sustainable agriculture. By supporting the efforts of small- to medium-scale sustainable farms, I seek to support efforts to move our civilization toward a more food secure and sustainable footing.

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