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A PHYSIOCRATIC SYSTEMS FRAMEWORK FOR OPEN SOURCE AGRICULTURAL RESEARCH AND DEVELOPMENT

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A Physiocratic Systems Framework for Open Source Agricultural Research and Development

BY

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DISSERTATION

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Dedications

This dissertation is dedicated to Bill Coperthwaite (1930-2013) whose insatiably open mind and belief in the power of sharing knowledge managed to both draw from history and be far ahead of its time. He was a true precursor to the current open source movement, and a source of deep personal inspiration and support.

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Table of Contents

List of Figures

Abstract

A Physiocratic Systems Framework for Open Source Agricultural Research and Development

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This dissertation presents a new participatory approach to agricultural research and development. It surveys the biological, sociological, economic, and technical landscape and proposes a framework for adaptive management based on the 18th century Physiocratic school of land-based economics. Industrial specialization and heavy emphasis on deductive approaches to science have contributed to the disconnection of large portions of the population from natural systems. Conventional agriculture and agricultural research methods following this pattern have created expensive social, environmental, and economic external costs, while adaptive management and resilient agricultural systems have been hindered by the cost and complexity of quantifying environmental services. However, the convergence of low cost computing, sensors, memory, and resulting data analytic methods, combined with new collaborative tools and social media, have created an exciting open source environment with the potential to engage more people in analyzing and managing our natural environment.

Introduction

Any contribution to science is of limited value if it cannot be replicated or built upon as part of the shared accumulation of knowledge and understanding; therefore, *the process of knowledge sharing* as well as the knowledge itself becomes part of the study (Karami, Keshavarz, and Lichtfouse 2010; Zaharia and Zaharia 2009; Jansson 2013).

> "This leads to calls for "innovative innovation" concerning the purposes and ways of designing new technologies and practices, or new practices in relation to existing techniques. In fact, these claims indicate a need for a shift in the governance of research and innovation to achieve a sustainable future" (Barbier, 2012).

The following work explores open source agriculture as an "innovative innovation" method of civic engagement in the exploration and inquiry of natural systems. The structural relationship between environmental management and biogeochemical feedbacks is at the core of this study. Technical, biological and economic intersections with social systems are necessary to act upon feedback; for this reason, the dissertation provides a historical context for interdisciplinary analysis as a crucial part of the systems framework approach to natural resources and earth systems science. The structure uses metaphors to bridge disciplines and to create an open source framework of biological, technical, and social systems upon which to support collaborative adaptive management.   Because of the interdisciplinary nature of this study, background that might otherwise be assumed common knowledge within a particular field of economics, ecology, agronomy, remote sensing, or software development has been included.

Figure 1 – A convergence of knowledge sharing technology and environmental documentation. This 3-D digital model of no-till hairy vetch plots, publishable through the Internet, documents crop variations in texture, volume and color. The existence and availability of environmental modeling and images created with consumer grade equipment illustrate the convergence of open source culture and low cost observation tools.

The word "Agriculture" is derived from Latin meaning "*culture* of a field." My study offers a framework to improve the sustainability of agriculture by examining the *culture* as well as the *cultivation* of the field, and to engage a larger segment of the population in that process. Ideally, the study will provide a systematic framework that fosters both inductive and deductive research to guide project design, analysis, and documentation.

Organization of the Study

The dissertation consists of three parts divided into a total of twelve chapters followed by a conclusion.

Part One, **Physiocratic Systems Framework** (Chapter 1: Systems Framework Literature Review, Chapter 2: Framing Agrarianism and Political economy, Chapter 3: Quantifying human interaction with the biosphere, Chapter 4: Technology, Open Source Culture, and Participatory Research, Chapter 5: Framework for Adaptive Management), outlines and places the active contemporary software-based collaborative adaptive management approach within a theoretical and historic social/political economy framework. This context will then be disassembled into systems components for more detailed analysis throughout the study. Particular emphasis is placed on the socio-technical process of gathering high frequency feedback required for the inductive research approaches implicit in adaptive management that will be referenced throughout the dissertation. The emphasis on inductive observations and feedback is matched with an accessibility analysis of high resolution, low cost, and impartial data sources.

Part Two, **Applied Collaborative Open Source Agricultural Systems** (Chapter 6: Open Source and Agrarian Systems Literature Review, Chapter 7: Application of a Physiocratic Framework: Case Based Studies, Chapter 8: Adaptive Management, Open Source Research and Social Media, Chapter 9: Agrarian Social Network Tools – Case Based Studies), provides applied examples of socio-technical structures modeled around the framework outlined in the first section of the study. The method builds upon the applied, inductive approach to systems analysis with case-based studies that explore the interaction of socio-technical agricultural systems.

Part Three, **Agricultural Research and Development** (Chapter 10: Technical Framework and Adaptive Management, Chapter 11: Technology Workflow and Illustrated Field Studies, Chapter 12: Low Cost Aerial Biomass Volume Measurement of Grain Corn Crop), provides a benchmark for contemporary technology and assesses the technological trajectory of accessibility, accuracy, and the cost of observation required for inductive research and adaptive management frameworks. Part Three also identifies technical challenges to filling in the adaptive management and social framework identified in the previous two parts of the study in order to achieve greater participation in environmental observations and agricultural research.

The study concludes with Chapter 13 as a Summary and Review. The purpose here is to create a road map for future interdisciplinary work that expands inductive and participatory observation and identifies the generalizable elements of adaptive management to address gaps, limitations, and challenges to resilient agriculture.

Background of the Study

Sustainability is not an absolute measure that can be imposed independent of human processes, but is rather a constant decision-making process that redefines itself in scale and time. The National Research Council articulated this complexity in a 2010 report titled *Toward Sustainable Agricultural Systems in the 21st Century*:

> "Pursuit of sustainability is not a matter of defining sustainable or unsustainable agriculture, but rather of assessing whether choices of farming practices and farming systems would lead to a more or less sustainable system as measured. Finding ways to measure progress along a sustainability trajectory is an important part of the experimentation and adaptive management process. Environmental, economic, and social indicators can be used to describe the performance of agriculture and to provide information on whether a farm, a farming system type, or agriculture at any scale is on a trajectory toward improved sustainability. Many indicators are means-based and others are outcome-based"(NRC, 2010).

Deductive agricultural research methods, dominant since the 19th century, have achieved many intended results, including increased yields; however, they have also created many unintended economic, environmental and social failures. Market failure is defined as a failure of the free market to distribute goods and services efficiently, including the idea that there is an alternative conceivable outcome where a market participant may be made better-off without making someone else worse-off (Gómez-Baggethun et al. 2010). Market failure reflected in undervalued ecosystem service functions and in external costs, or externalities, is partly the consequence of non-systems approaches. Conventional resource management practices are a symptom of the dominant culture not internalizing environmental values into market structures, which has led to global scale market failures and tragedies of the commons such as soil degradation, water pollution, and surplus atmospheric C02 (Ruhl, Lant, and Kraft 2008; Hamilton et al. 2007). The National Research Council also argues that pollution of water, soil, and air, degradation of environmental resources, and loss of biodiversity are the by-products of current agricultural systems and identifies additional external costs such as global greenhouse gas emissions and a myriad of public health problems (NRC, 2010). Such externalities have left farm productivity and economic viability vulnerable to resource scarcities, climate change, and market volatility. Sustainable agriculture, in the National Research Council's view, has emerged largely in response to the market failures of modern "industrial production" agriculture.

Agrarianism and Agriculture as a Social Science

Agriculture is a human activity; therefore, its application and practice are as much a product of social ecological systems and values (Walker et al. 2002) as of technical or biological limits (Ledermann T. 2008; Uri 2000). However, the cultural component of agri*culture* is often understated, not just cultural practices of crop rotation, but the culture of the civilization that agriculture supports and is supported by. The focus has instead been placed on physical, economic and chemical/biochemical processes, e.g. fertilizers and pesticides and genetics. Because of the clear role of social limitations in the practice of agriculture, a *techno-biological approach alone is not sufficient* (Sakai 2009; Karami, Keshavarz, and Lichtfouse 2010;

Zaharia and Zaharia 2009); rather, the interaction of social context and practices with technological and biological aspects of agriculture is crucial to managing agricultural systems.

Agrarianism as a social movement internalizes the integration of biological, social, and technical aspects of agriculture into cultural values of land management across the general population. Historian Richard Hofstadter notes that to call American agrarianism a "myth" of sentimental attachment is not to imply that the idea is simply false. Rather, the *myth* so effectively informs an agrarian ethos that it profoundly influences people's values and behavior (Hofstadter 1955).

Hofstadter emphasizes the importance of the agrarian myth even after industrialization revolutionized the American economy and life. Recent, improved environmental monitoring of agricultural pollution has brought to light practices that run counter to the agrarian ethos with examples such as the Gulf of Mexico “Dead Zone”, the decimation of the Chesapeake Bay estuary, and identification of agricultural runoff as causing algal blooms in Toledo, Ohio that have poisoned drinking water supplies. Tellingly, these examples have not crushed the agrarianism myth, but have rather exposed the abuse of that myth by commercial interests that market an idyllic, diversified image of agrarian heritage while profiting from extractive practices. The deviation of the agrarian myth from the dominant reality of contemporary production agriculture is evident in almost any children’s book that depicts images of diversified farms, rural culture, and local markets. These idyllic, agrarian images are significant in their contrast to the well documented trends towards concentration of ownership and extractive, input-intensive production patterns of contemporary agriculture known as factory farming, captured by the famous admonition of USDA secretary of agriculture Earl Butz in 1977 to “Get big or get out” (Kleiner 1986).

Managing the agrarian myth through the internalization of shared values in the broader culture is crucial to creating sustainability and to reducing negative externalities. It requires developing cultural myths and metaphors that internalize whole systems accounting. The desire for creating a new story of people and the land is reflected in the contemporary local food movement, which, at its essence, seeks greater accountability and connection to shared cultural values that are not being fulfilled by the contemporary industrial agricultural system (C. A. King 2008).

A classic example of this mismatch occurred when former Secretary of Agriculture, Earl Butz, and poet-farmer-New Agrarian, Wendell Berry, squared off in a debate. In his rebuttal Butz remarked, *"I've got a feeling that Dr. Berry and I haven't met here tonight. Perhaps we won't."* Berry later commented, *"We may never meet because he's arguing from quantities and I'm arguing from values"* (Beus and Dunlap 1990). The history of agrarianism has involved the internalization of these values across the culture including the highest leadership. The *Encycopédie*, the definitive work of the Enlightenment published in 1751, lavished attention to the mechanical arts such as agriculture and explored the cultural historical significance of agrarian values in societies. For example the Chinese emperor and his highest advisors would host an annual ritual by taking turns at the plough turning the first furrows of the season, generals in the Roman Republic would return to their yeomanry as their preference over lives as politicians or merchants, and the physiocrats convinced the future Louis XVI, 'the ploughing dauphin' to imitate the Chinese ritual by following a plough in a sowing ceremony on 15 June 1769 (Cronk 2006). A faint legacy of these rituals, and values, can be seen in the White House garden installed by the Obamas during their first term.

Systems Dynamics and Adaptive Management

Adaptive management is a complex ecological and socio-technical process, and requires a collaborative approach in which multiple stakeholders participate in learning and developing a shared understanding of a process of incremental experimentation and feedback with adaptive goals, objectives, and management decisions. Adaptive management can also be described as ongoing observation-based research and development integrated into a management process. Adaptive management in agriculture, therefore, requires the involvement of farmers in the research and development (R&D) process, and usually leads to the formulation of a systems diagram often framed as a tree of problems and opportunities, with many ramifications, rather than as a single clear-cut issue.

Key differences between farmer and scientist problem statements stem from farmers' integrated, holistic, and observational approach to farm and resource management as opposed to that of discipline-oriented scientists, who are taught to break problems into manageable parts. The laboratory scientist's deductive approach to scientific inquiry, which isolates theories out of the field in order to test hypotheses, is often viewed as irrelevant by the farmer and agrarian. Collaborative adaptive management following a Physiocratic framework has the potential to productively bridge laboratory science to applied agricultural research.

Systems by their very definition have emergent and dynamic qualities which make precise and stable definition challenging. Barbier (2012) articulates this challenge well (emphasis added):

> "System innovations are multi-factor, multi-actor and multi-level (multi-scaled) processes, and can only be understood through the ***historical co-evolutionary processes which link up these actors, factors and levels***. These historical processes are riddled with uncertainty and constitute open-ended learning processes. Influencing such processes has proved to be difficult, but not impossible. To stimulate sustainable development, the challenge lies in influencing development at an early stage, when irreversibilities are not yet entrenched and one can hope to sway the balance between desirable and undesirable development processes. Researchers on system innovation, knowledge regimes and design practices in the agro-food sector can be seen as pivotal examples of what Gibbons et al. (1994) called a mode 2 type of knowledge production. It transcends traditional disciplinary science in two ways, viz: (1) it combines insights from various disciplines and (2) knowledge is generated in a combined effort by scientists and stakeholders from the domain under investigation."

The framework of systems thinking provides a method to describe and study complexity, and "transcend disciplines" and has developed into the applied science of adaptive management (Karami, Keshavarz, and Lichtfouse 2010; Folke et al. 2002). Adaptive management is an approach for addressing human environmental feedback loops, and is a systematic process for continually adjusting policies and practices by learning from the outcome of previously used policies and practices. Adaptive management uses each management action as a scientific experiment designed to test hypotheses and to "probe" the system as a way of learning about the system. Collaborative Adaptive Management (CAM) is the coordination of these efforts across social and geographic scales to achieve greater feedback, accuracy and effectiveness (Susskind, Camacho, and Schenk 2012; Susskind, Camacho, and Schenk 2010). My study explores the systems contexts required to incorporate meaningful quantitative interdisciplinary observations that can be used for CAM.

Any transformative approach to change must therefore build on an understanding of agriculture as a complex and technical socio-ecological system. In this context, technology is not the sole solution to the challenge of internalizing external costs; however, *technology informed by ecological, social, and economic feedbacks can create the social conditions for transformative change.* Barbier (2012) states that "Technical change is always a complex process with both biophysical and socio- economic aspects. It results from changes in the thinking and activities of individuals, households and communities, as well as in market and organizational relationships. In such transitions, learning is applied to new systems of behavior and valuation, not just techniques or methods (Barbier and Elzen 2012). However, cultural change, like evolution, is incremental and therefore needs stepping stones to move from one dominant form to another (Kelly 2010). Technology can aid this process and make a more participatory, social, and inductive approach to inquiry possible by providing large quantities of impartial data to draw upon to quantify environmental systems. The case studies and applied examples in Part Two and Three, below, are based on this social approach of "probing" the system for observable responses and feedback.

Quantification of Environmental Services

Describing the human interaction with nature through labor and land management has a long and challenging history (Higgs 2001; Costanza 2012); the complexity inherent in quantifying and articulating the balance between human labor and nature's contributions to productivity has led to oversimplifications of systems descriptions. The resulting externalities and market failures previously mentioned help frame the following three problem statements:

(1) The economies of scale of industrialization and globalization have removed large segments of the population from interaction with natural systems due to overspecialized social and economic institutions (Johansson, Kisch, and Mirata 2005).

(2) The cost and complexity of deductively quantifying human interaction with the biosphere and ecosystem services has been a primary reason for the lack of quantification and resulting externalities (Kroeger and Casey 2007).

(3) The pace of technology to monitor and observe human changes to the biosphere has lagged behind both the pace of industrially extractive technologies and the ability to change our environment (Ernstson and Sörlin 2013).

Purpose of the Study

The purpose of this study is to increase our understanding of environmental and natural resource problems and solutions at local, regional, and global scales and to pursue interdisciplinary research of the environment. My dissertation proposes a historic Physiocratic framework to address the three problem statements above, and to contribute to a better interdisciplinary system for agricultural research and development. The study explores the intersections of emergent open source social, technical, and biological systems with a trajectory of powerful low-cost tools to observe, access, and communicate knowledge, making collaborative adaptive management possible. Furthermore, the study explores how these factors can positively disrupt market failures with quantified feedback acted upon through collaborative adaptive management and internalized into environmental service values.

Summary

Both the global environment and our understanding of that environment are changing at rates that are unprecedented in the history of the Earth. Solutions to environmental problems require knowledge of the interaction among physical, biological, environmental, socioeconomic, and cultural factors that underlie the identification of environmental problems and choice of action. The following twelve chapters will present an interdisciplinary systems analysis using social case study, historic political economic analysis, and examples of field data collected to illustrate an inductive, technical workflow within an adaptive management framework. A workflow consists of an orchestrated and repeatable pattern of activity enabled by the systematic organization of resources into processes that transform materials, provide services, or process information.

Section I: A Physiocratic Systems Framework

Chapter 1: Systems Framework Literature Review

Chapter Introduction: Historic Roots of Agrarianism and Political Economy

Biological systems that support human civilization can be influenced to produce more or less of the services we need based on our care and management. Natural resources and their management have always been central to the study and understanding of human civilization. The roots of political economy included the study and interaction of humans and their environment, and were formed in pre-revolutionary France by the first land-based economists. These natural philosophers, called "Physiocrats" from the Greek *phusis* (nature) and *kratos* (power), introduced a scientific approach to political economy and proposed that only agriculture can generate an economic surplus through the productive powers of land, and that through greater knowledge of natural systems, people can improve the productivity of soil and the health and wealth of a nation (Higgs 2001). Their observations of the interaction of civilization and soil over 200 years ago are as relevant today to understanding the Anthropocene as the Greek philosophers' moral queries raised over 2000 years ago that form the basis of modern law. The Physiocratic school of thought also grew out of Enlightenment thinking and Confucian agrarianism, and was characterized by a particular optimism that the world could be understood and improved through inductive observation and human engagement with nature. In particular, the key tenet of Physiocracy was the improvement of soil to increase the wealth of a nation (Gómez-Baggethun et al. 2010; A. Smith 1776). These first economists worked without the benefit of the knowledge of chemistry and mechanisms required to build the periodic table; however, they observed people and nature through indicators, such as the interactions of social and soil conditions, plant life and the health of farmers, laborers, merchants and landlords, and the circulation of resources across a landscape. Their limitations in scientific observational methods naturally limited their available scientific approaches. Without established theories and a body of scientific findings to draw upon, their approach necessitated insights and inductive theories generated through observation of broad systems behavior (Fuller 2004).

The outcome of the natural philosophers' inductive method yielded systems-wide observations that still have cultural, biological, and technical relevance today. It is becoming increasingly clear that the technical achievements of our post-industrial society, used out of context from whole systems analysis, will not necessarily result in a more sustainable society, i.e. a society that is characterized by a better balance between economic, social, and ecological goals. Ensuring that any transition potentially taking place leads to greater sustainability is a major challenge for agro-techno-social food systems in particular, and one which calls into question the relations between sciences, agricultural technologies, and public or private networks that make up the environmental system. Thus the need for a whole systems approach, with methods for communication and a framework to manage “innovative innovation” in studying these systems (Barbier and Elzen 2012).

Quantification of Ecosystem Services

For most of human history, inductive methods were limiting to scientific progress, but were also the more accessible approach. Because inductive reasoning relies on impartial observation and recording of details about management, it was subject to inherent biases of both the observational and communication technology to process personal observations and farmer-to-farmer knowledge exchange. The advent of the printing press enabled the accumulation and exchange of observations, although observations were still limited by frequency and the skilled eye of the observer (Mulla 2013) and exchange was limited by access to information. English agricultural innovator Jethro Tull's observations were still considered novel 50 years after he made them, when they were finally translated and republished for wider distribution (Diderot 1751). The advent of lenses, photography and chemical analysis expanded resolution of observational technology, but by itself did not provide the context for functional relationships of systems indicators (D. E. Allen et al. 2011; Idowu et al. 2009). It was not until communications and archiving of scientific work resulted in a compounding effect of deductive and inductive approaches that the pace of scientific discovery increased. My study will explore how, despite increased understanding of biological mechanisms, inductive systems based studies are still crucial to closing vast gaps in technical socio-ecological system understanding of the interaction of these mechanisms in agriculture.

Until recent technical developments, the limitation in knowledge flow rather than observational technology has limited the quantification of environmental services and the resulting feedback required for adaptive management. The AdaptN software decision support model for adaptive nitrogen management, developed by the Cornell Soil Health Laboratory, is a notable exception. Other than a handful of examples, adaptive management has yet to be widely adopted for large scale agricultural systems, in large part because environmental feedback of sufficient resolution has been too costly or complex to measure (Van Es and Degaetano 2008)

Transformative Observation Technology

The first LANDSAT satellite was launched in 1972 and ushered in a new cultural awareness of Earth systems based on remote sensing. However, it has not been until the recent convergence of open source culture, and networked, low cost computing, sensors, accelerometers, gyroscopes, GPS, and memory that the temporal and spectral resolution have the potential to radically shift cultural understanding of natural systems (Xiang and Tian 2011). These compounded technical achievements have made possible observational technology and inductive inquiry enabled by computer processing and big data methods, coupled with collaborative tools to create a research and development environment that has the potential to radically alter public awareness of our natural environment.

These recent, rapid changes in technological accessibility have yet to be culturally incorporated into agricultural management or applied to accurately monitor and model ecosystems. Technological developments have been applied only in a limited way to conventional large scale precision agriculture and primarily to increase monoculture accuracy and efficiency; the benefits of remain out of economic reach for smaller producers (Bakhtiari and Hematian 2013; Mulla 2013). The dramatically lower costs of memory and power storage, motors, controllers, sensors, radio communication, and public access to consumer grade cameras, smart phones and other devices has yet to be assimilated into diversified agriculture.

The application of these tools in diverse agriculture and environmental monitoring have the potential to be transformative (Silvertown 2009; Newman et al. 2012). New technologies dramatically increase the temporal frequency of observations as well as decrease the cost per observation, and enable monitoring beyond the human sensory range (Hunt, Jr. et al. 2010). They produce documentation in a form that can be shared without degradation across space and time at a marginal cost of near zero. The low cost and large benefit of sharing code has benefited open-source software. Until recently, customizing software has been much easier than custom-building equipment; the open-source paradigm is now enabling the creation of open-source scientific hardware, as well (Pearce 2012).

A transformation of popular culture through ubiquitous observation, communication, computation and data storage introduces the possibility of regenerative adaptive management being within reach. These factors create conditions that can soften the boundary of professional science characterized by reductive hypo-deductive processes. The history of interdisciplinary amateur citizen scientists provides an alternative road map to research that draws on inductive reasoning. Here, I explore a framework, tools, and approach that critically assess the potential for *every farm to be a research farm and every backyard a laboratory*. The techno-cultural shift made possible by ubiquitous, inexpensive, accurate technology forms the basis for this study to help meet the challenge defined by National Research Council to *assess and measure progress along a sustainability trajectory* and to build a social framework to support those efforts.

Social Dynamics of Innovation

This dissertation uses a case based approach to both frame and place in context broader systems observations. The interaction between technological, social, and biological systems occupies a great portion of the study. Barbier (2012) describes innovation as crucial to the transition towards sustainable agro-food systems, stating that:

> "This typically implies technological change, for a host of new technologies will be needed to meet the sustainability challenges in the various agricultural subsectors. Technological change, however, will not be enough. The enormous challenges lying ahead will also require new regulations, new behaviours (e.g. of consumers, farmers as well as many other stakeholders), cultural change, institutional change, institutional 'hybridicity' and the ecologization of agricultural sciences and technology (Barbier and Elzen 2012)."

While the term 'system innovation' may denote broad technological change, innovative design in the socio-economic order of agro-food systems is also part of system innovation. System innovation phases and patterns is subject to the adaptive cycle of change (Holling and Ludwig 1995) described in Chapter 3. Economic, biological and technological systems may not always move through adaptive cycles at the same rate. For example, technology may move more quickly, and established actors that benefit from current regimes may resist change, or disruptions. Conversely, 'outside' actors attempting to create new niches may see the disruption as an opportunity rather than a threat. Actors working to establish new niches may investigate more radical solutions and learn how to make them work, technically as well as within the framework of consumer requirements, markets, and regulations. Barbier (2012) adds that "if successful, these "transition" developments may link up to an existing regime and gradually change or replace it, which can eventually lead to system innovation. In this process, niches therefore play a crucial role."

Chapter 2: Framing Agrarianism and Political Economy

Mirabeau's Tree: A Systems Metaphor and Social Framework

The use of metaphor as a framework for systems study has a long history within political economics, and indeed metaphor is crucial to the framework of this study (Carpenter et al. 2001; Gómez-Baggethun et al. 2010; Costanza 2012). Herman Daly observed:

> "That economists have also found biological analogies useful is only slightly less obvious. The circular flow of blood and the circular flow of money, the many parallel phenomena of specialization, exchange, interdependence, homoeostasis, and evolution are well known. In the opposite direction, economic analogies in biology are also common, as witnessed by Malthus' influence on Darwin and by the very etymology of the word "ecology" (Daly 2012).

Because their own knowledge was neither quantitative nor scientific in our modern sense (the term "scientist" was not used until 1834) (Ross 1962), the Physiocrats relied on metaphor to describe systems behavior to the Court and general population. In 1757, Francois Quesnay, a founding Physiocrat, used a metaphor that will form the theoretical foundation and social framework for the remainder of this study:

> "The state is a tree, agriculture its roots, population its trunk, arts and commerce its leaves. From the roots come the vivifying sap drawn up by multitudinous fibres from the soil. The leaves, the most brilliant part of the tree, are the least enduring. A storm may destroy them. But the sap will soon renew them if the roots maintain their vigour. If, however, some unfriendly insect attack the roots, then in vain do we wait for the sun and the dew to reanimate the withered trunk. To the **roots must the remedy go**, to let them expand and recover. If not, the tree will perish." (emphasis added)

Quesnay was quoting an earlier Physiocrat, Victor de Riqueti, Marquis of Mirabeau (Bauer 2012; Higgs 2001). Mirabeau's tree metaphor keenly integrates social, technological, biological and economic feedbacks to create a relational structure within a larger agro-ecological system that still holds up to a contemporary understanding of biogeochemistry, economics, and sociology. With this quote, Mirabeau formed the conceptual foundation for Physiocracy which, in turn, formed the basis for subsequent schools of political economy. Physiocracy's influence is still clear on USDA buildings around Washington DC. Until November 16, 1983, the US Department of Agriculture seal's official banner read "agriculture is the foundation of manufacture and commerce"(USDA 2002).

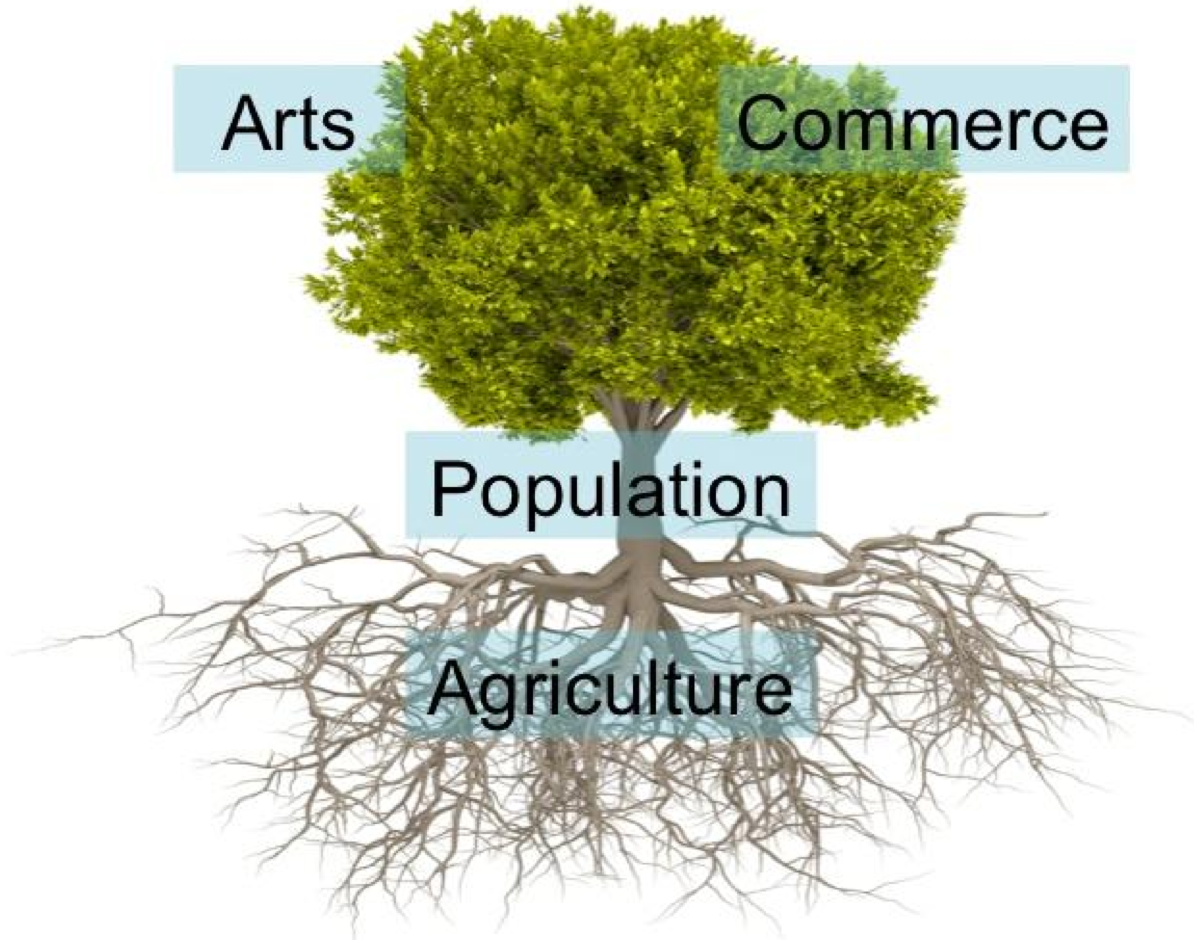

Figure 2 – Introduction of Mirabeau's Tree. The tree metaphor forms basis for the Physiocratic Framework for adaptive management that is used throughout this study. Mirabeau uses the tree as a living system to describe the state (as a unit of civilization), with agriculture at the roots. Physiocrats believed that agriculture and the improvement of it, provides the regenerative growth capacity for the state and the primary renewable source of wealth for its citizens.

Mirabeau's tree metaphor is illustrated, annotated, and expanded upon throughout this dissertation to position and create context between aspects of the interdisciplinary study. It is used to map the relationships of technological evolution, flow of information, and innovation as a natural circulatory system within the context of biogeochemical cycles and illustrate the political economy not just as social science but as a life science as emphasized by ecological and environmental economics (Davidson 2012; Herman E Daly 2012). Figure 3 illustrates the tree's natural systems function encompassing the concept of nutrient flows and circulation as both a metaphor for inner circulation - i.e., within the tree and social science aspects - and external nutrient flows of biological sciences and economies within the larger biosphere and related feedbacks between the political economy and ecological systems.

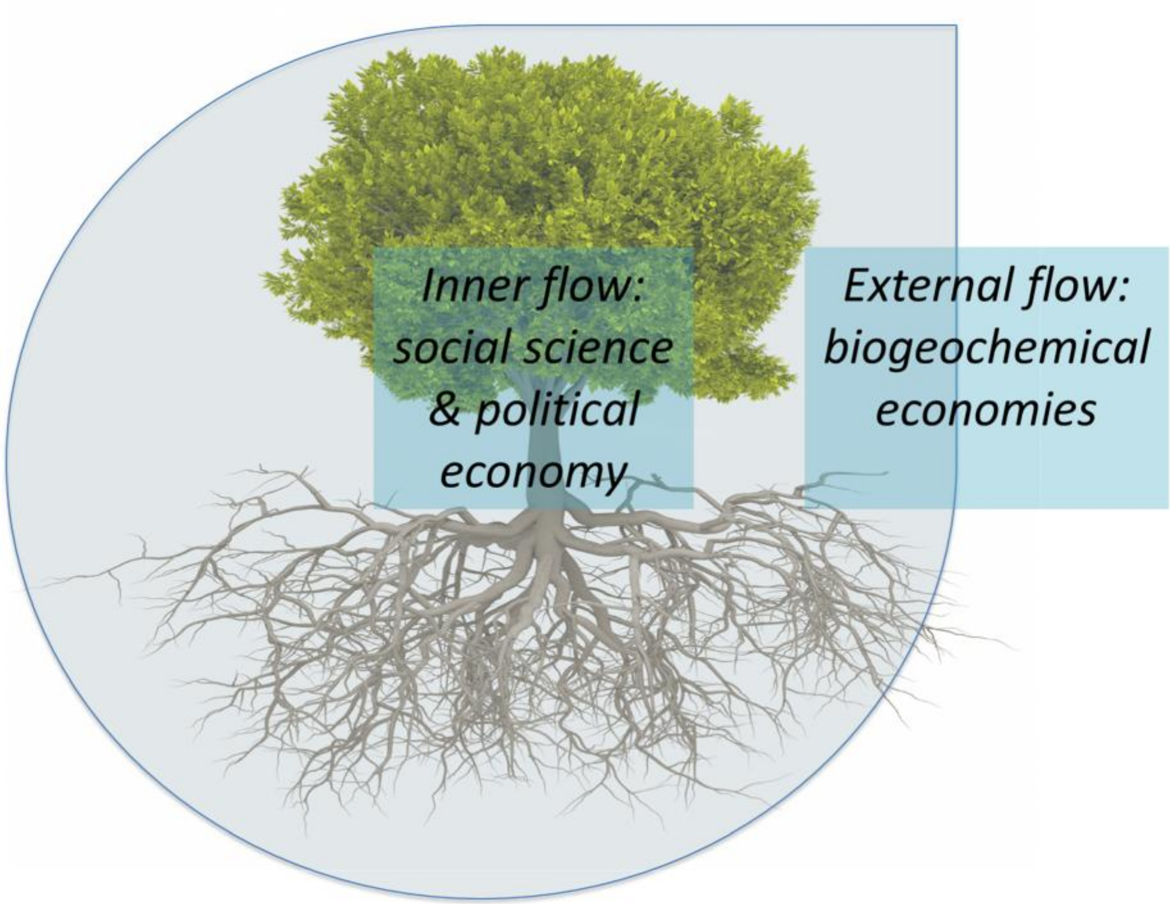

Figure 3 – Mirabeau's Tree provides interdisciplinary context. Mirabeau's Tree also illustrates the functional relationships between areas of science. The interdisciplinary nature of the metaphor is useful to position the study of political economy within a bio-geochemical system, indicated by the outer grey shading. The concept of the Anthropocene, or age of man, is interpreted as the effect of Mirabeau's tree on the surrounding environment. The metaphor also illustrates the concept and relationships between social science and environmental science required for whole systems understanding by an engaged and informed population.

The tree metaphor also differentiates and invites analysis of types of growth within the system, including its sources, vulnerabilities, resilience, adaptation, evolution, and feedbacks within related systems. In particular, a tree provides a method of differentiating and positioning unproductive growth from productive growth by illustrating the location and relationship of the growth to a structural position and importance of inquiry in different areas, i.e., whether the inquiry is located at the tip of a leaf, or at the base of the trunk.

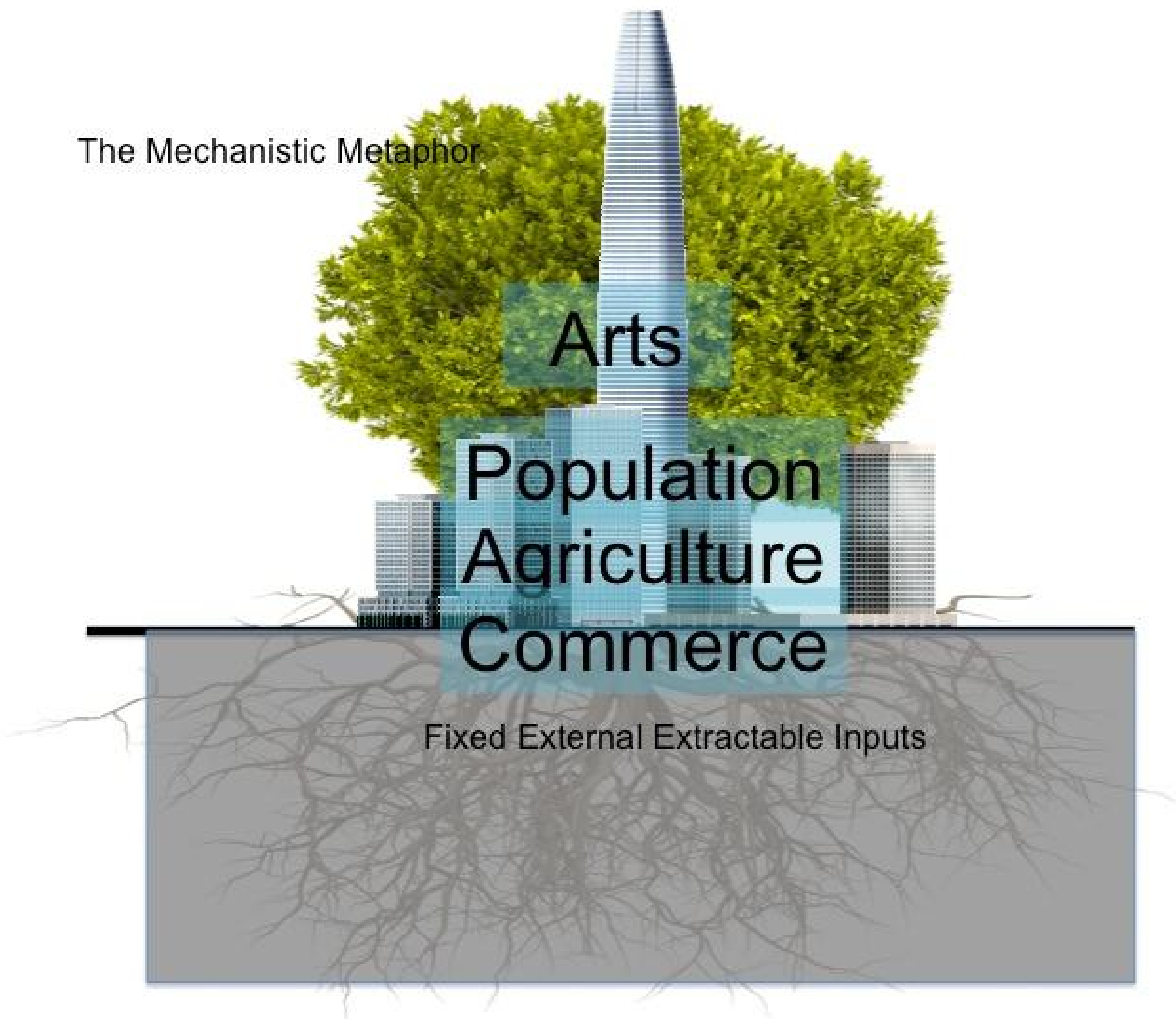

Figure 4 – The mechanistic approach to nature subverts agriculture as a subset of commerce. Industrial development economics ignores the role of ecosystem services in supporting economic activity, and treats nature primarily as a fixed resource, as illustrated in this diagram by obscured and greyed-out roots of Mirabeau's tree. Agriculture in this model is not based on regenerative growth, but on a cost of inputs produced by capital (i.e. labor and capital), and neglects and therefore does not account for the productive capacity of nature. The result is a general population disconnected from the biogeochemical systems and essential ecosystem services. The

political power dynamics of this model are therefor also inverted, resulting in the undervaluing of land-based economics.

Locating human endeavors and relating them to structural economic areas within the larger system provides a framework for additional insight. Systems health is not so much an exercise in measuring absolute values but in measuring relationships, balance, and resilience. The structural metaphor of the living, breathing, growing tree communicates these functional relationships and quantifies flows between structures. The systems health indicators measure growth as well as balance and resilience, factors that are missed by mechanistic measurements based only on commerce such as extractable stocks or Gross Domestic Product (D. Meadows 1998; D. Robinson et al. 2013; Stockhammer et al. 1997).

The specialized language developed within environmental and earth science disciplines have created cultural barriers to expanded engagement and participation (Couvet et al. 2008). To create crossover, the intuitive language of Mirabeau's Tree offers a context for problem statements by placing efforts within a larger systems context that can be used to develop and translate standards of measurement. By necessity the metaphor is abstract, but the abstraction is also a strategy to communicate beyond the comfort zone fostered within the specialist professional science culture, and to facilitate interdisciplinary problem statement overlap. It also implies and requires reaching outside of the existing incentive structures of contemporary academic and organizational structures. The intuitive metaphor of Mirabeau's Tree and the Physiocratic framework from which it stems serves a crucial role of building cultural trust and shared values between professional, deductive methods of science and the more exploratory, inductive approach of open source communities.

The dynamic tension between inductive and deductive scientific inquiry was quite current at the time that Mirabeau's tree metaphor was authored and was discussed at length by Darwin (Lightman 2009). The Enlightenment values of shared knowledge and the importance of inquiry itself are made current with adaptive management approaches that explore the use of environmental and social data that can now be collected, not by individual researchers, but by millions of citizens and unbiased sensors. Mirabeau's tree metaphor serves as a boundary to represent the whole system, and places the millions of potential observations and contributions within a relatable social, biological, and technical system context, that would otherwise be overwhelming to contemplate and communicate. In the sense that it is collaborative and exploratory, the model itself is a form of embracing an inductive approach to scientific inquiry.

Natural Resource Management within the Framework

Expanding biological productivity is the explicit role of larger geochemical cycles that support soil formation and fertility and are crucial to supporting resilient growth. Because Mirabeau's tree metaphor is based upon a living system it also welcomes the measurement and evaluation of systems "health." The definition of *soil health* is the capacity for soil to function biologically, physically, and chemically (NRCS 2014). Within Mirabeau's tree metaphor, soil health is crucial to the health of the root, and forms the foundational anchor of the system. The metaphor is a powerful tool that communicates complex ideas implicitly with associations in a simple relatable form, without which explicit descriptions and associations are required. The tree metaphor is an illustrated version of the Physiocratic framework that is both simple to understand *and* communicates complex ideas. It is used as tool throughout this study to reference and relate the positioning of relationships between interdisciplinary systems for case studies and analysis.

Chapter 3: Quantifying human interaction with the biosphere

Biogeochemistry and Agriculture: Quantification and Description of the Current Measurement Regime

Human understanding of our environment is reflected in the tools created to observe it. Population pressure on degraded land has pushed environmental systems closer to thresholds, or to a point where other land must be managed to sustain a condition beyond "natural" unmanaged thresholds, and requires constant upkeep (e.g. terraces and irrigation). Additional pressure creates more complexity and urgency to add systems management sophistication before passing over thresholds into new, less productive regimes (Walker and Salt 2006).

The cost and complexity of quantifying human interaction with the biosphere and ecosystem services has been a primary reason for a lack of systems quantification, and has given precedence to the lab-based, deductive approach to scientific research. With limited resources available, building on the known is less risky than exploring the unknown. Additionally, the professional scientific culture has undervalued the participatory, observational contributions made daily by farmers in the field. For most of human history, humans have been limited to describing the environment with the unaided eye, which is limited both in perspective and spectrum. The invention of the microscope and telescope expanded the field of view but not the perspective. It was not until aerial imagery that we were able to radically change our perspective and see beyond ourselves by looking out and down at our place in the world; these aerial imagery tools enabled the ability to look at larger environmental and land use patterns and put ourselves in that larger context. Satellite imagery has further extended this range of perspective. Because of complexity and cost, this type of aerial imagery has been inaccessible to the broader public. However, observations without a systems context do not communicate the complex effects - negative and positive - of human economic activity on the landscape. Because of complexity and cost, this type of aerial imagery has been accessible to only a select few in government or corporate laboratories over the last 50 years; likewise, the balance between systems based observation and deductive approaches to scientific environmental inquiry has not shifted until recently because of the cost and complexity of analyzing large scale data collection.

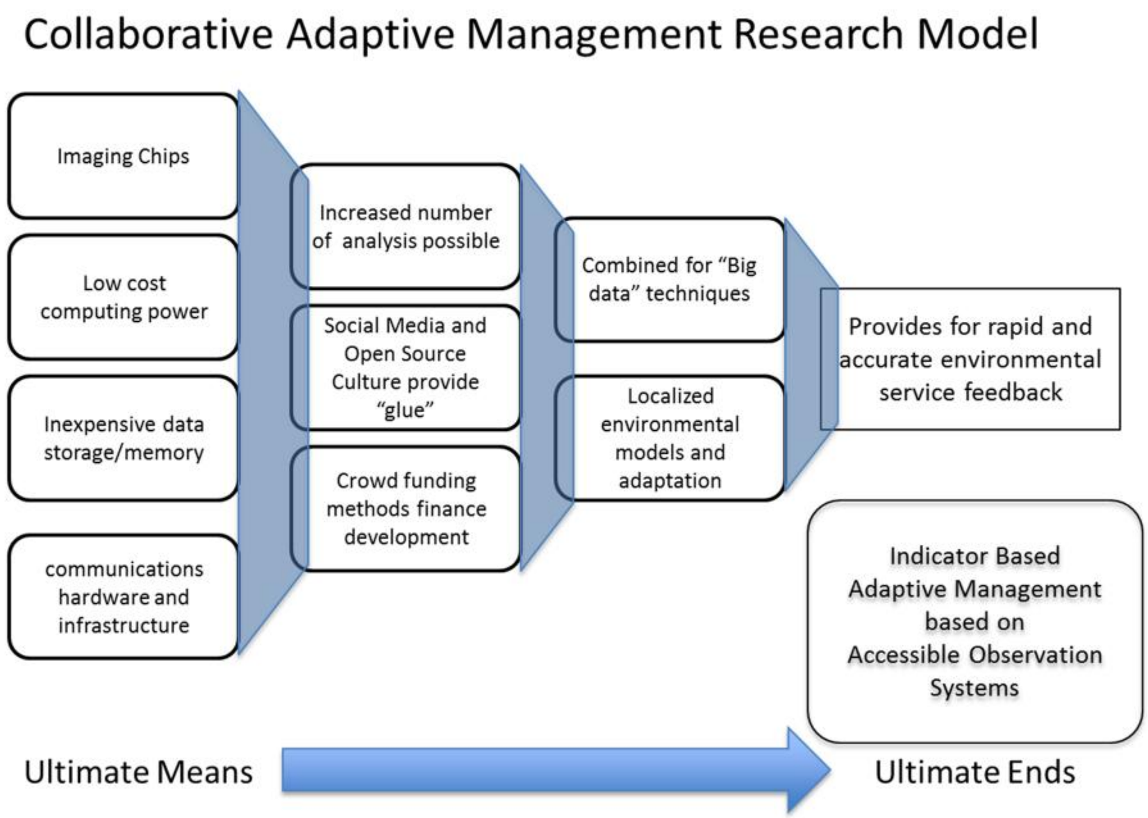

Figure 5 – The convergence of culture and conditions and their relationship to adaptive management. The flow and convergence of culture and technology is illustrated as a means of addressing challenges of high frequency feedback required for adaptive management. Cost and accessibility are both barriers to greater levels of observation. Also illustrated are the building blocks and sequences required to achieve the desired state of public internalization of environmental service values.

Recently, global remote sensing has dramatically improved the resolution and accuracy of landscape level modeling. However, the social and technical challenges of increasing the resolution beyond regional planning to enable watershed and smaller landowner/farmer level decision support has yet to become a reality (Mulla 2013).

Complexity in describing nature has led to the associated costs of undervaluing ecosystem services (Kroeger and Casey 2007). Biological systems level measurement has been ignored because of cost and technical challenges and, in part, because compartmentalized, deductive methods of building on known theories has been a more accessible and acceptable approach than inductive exploration into unknown, as yet untested, or untestable theories. The cost and complexity assumptions are now changing. Figure 5 illustrates the generalized flow of technology and data as an intermediate means to the ultimate ends of better resource systems understanding (and human happiness). Figures 6 and 7 illustrate examples of how these changes in observational technology are expressed in the form of environmental imagery. Environmental systems understanding is not static, and the technical accessibility, cost, and accuracy of measurement changes radically with cultural assimilation and associated skills that develop roughly in parallel with new technology.

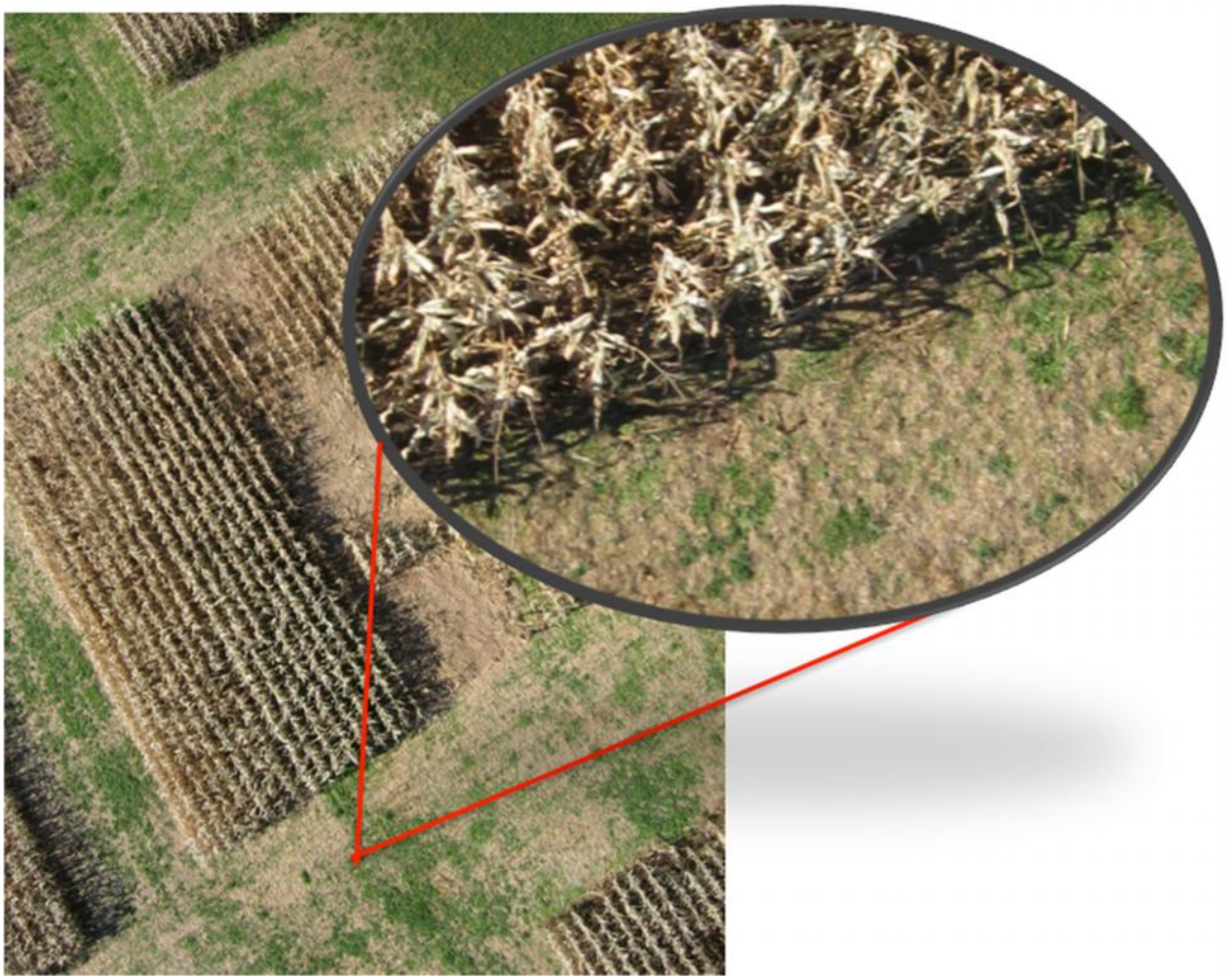

Figure 6 –High resolution digital imagery as an example of adaptive tools. The image represents an intermediate output of the adaptive management model illustrated in Figure 5. Low cost consumer grade observation tools now enable high resolution aerial images accessible to the general public and farmers at any scale. The low equipment cost also makes higher frequency observation more practical than previous observation methods. The zoomed in outtake in figure 6 illustrates that 5cm resolution enables the identification of individual corn plants and leaves. The accessibility and resolution of observation tools is a key element for adaptive management feedback to be useful to farmers.

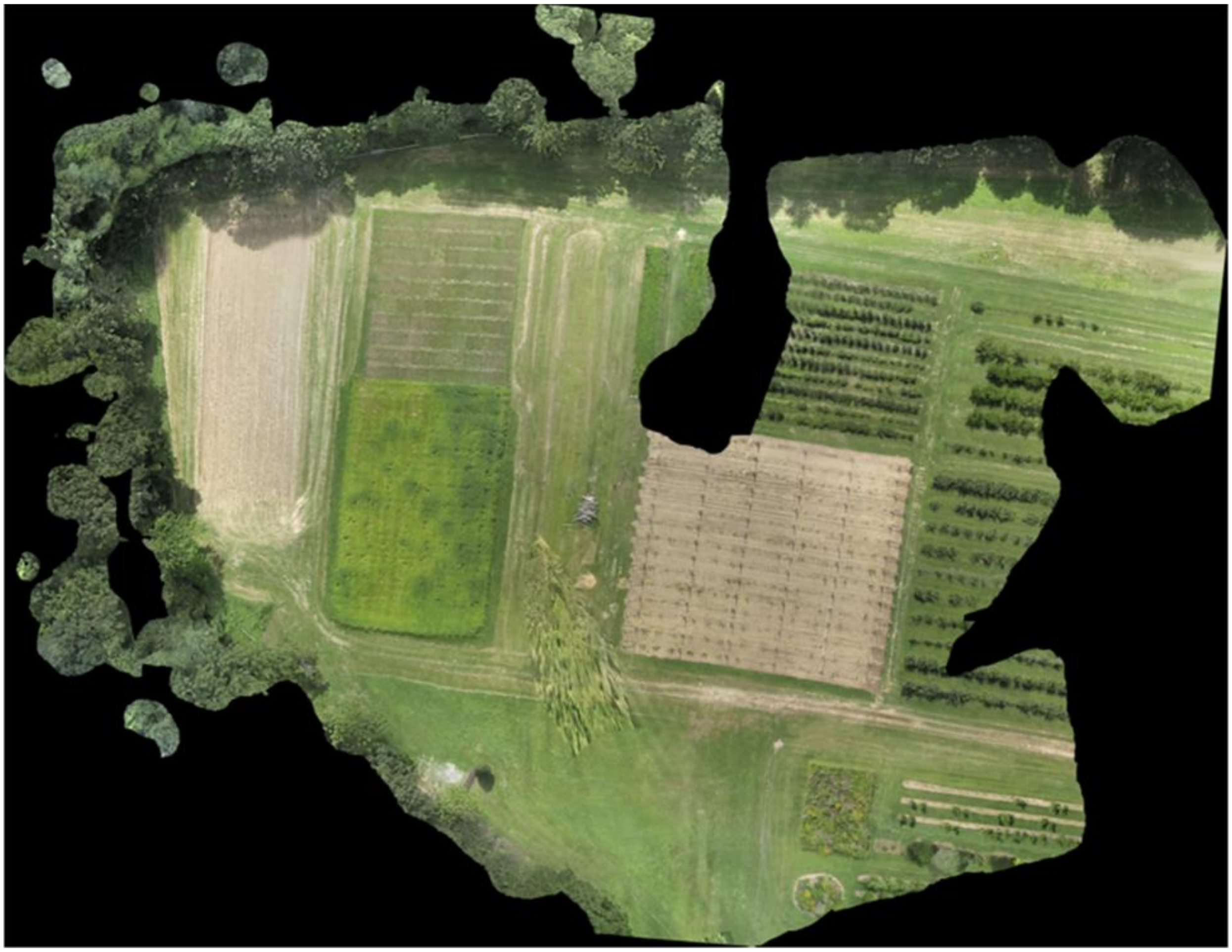

Figure 7 – Changes in perspective reveal patterns useful for management. This 3-D model was generated from still images, and also represents the convergence of technology and culture described in Figure 5. Low cost computing power, image chips and memory enable complex operations such as image stitching and analysis to be performed in the field with a consumer grade laptop. The image also represents an expansion of the capacity of an individual farmer to change their perspective when observing their own land, and observe patterns from leaf level (as illustrated in Figure 6) to the landscape perspective, illustrated here. Each level of observation reveals different patterns difficult to observe and quantify from the ground level. In this image, the dark green patterns in the sorghum sudan grass (lower left block) reveal soil nutrient variation caused by the previous year's cropping practices.

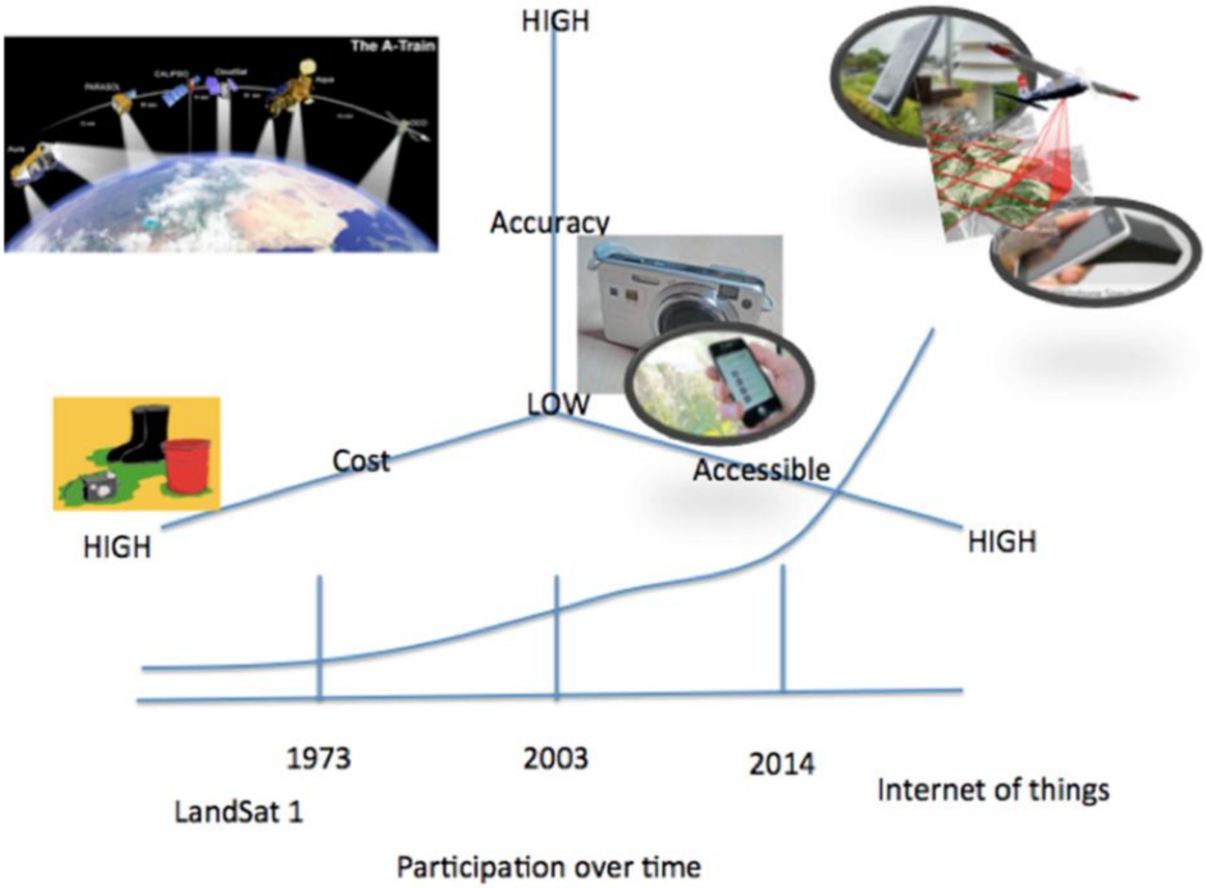

Figure 8 - Technical milestones for observation technology. The images represent technical milestones, and the three axes represent the trajectories in cost, accessibility and accuracy of those milestones. The resulting participation is indicated as a behavior over time (graph at the bottom). A goal of scientific inquiry is a more informed and engaged population. The three axes illustrate the transition of scientific observation technology from tools that were expensive, not very accurate or accessible (lower left quadrant), to a proliferation of powerful easy-to-use tools available at consumer prices (upper right quadrant). Note the proliferation of observation technology made possible by a dramatic decrease in the price of imaging chips, computing power, memory and communications costs that, if harnessed together, can produce a trajectory and desired state of low cost, highly accessible, accurate tools with high participation.

Figure 8 graphs observational tools along several axes: Cost, Accuracy, and Accessibility and the rough balance of these factors over time. The right, upper right quadrant is projected as aspirational with large participation, high accuracy of observations, low cost per observation and highly accessible.

Prior to the first television images broadcast from space in 1960, and then digital imagery from LandSat 1 in 1973, aerial imagery was the only option available for remote sensed imagery. Aerial imagery at that time remained higher resolution but also at a far higher cost. The launch of observation satellites began the cultural transition reflected by Marshall McLuhan's now generally forgotten claim that 'at the moment of Sputnik the planet became a global theater in which there are no spectators but only actors'(McLuhan 1974). His claim that the earth became a form of art is even more fitting when we consider that Google Earth's interface realizes McLuhan's metaphor in the detail and context anticipated 50 years earlier.

Until about 1973, observation of the earth was limited to aerial imagery and physical samples taken by hand. LandSAT1 launched in 1973 and began the process of monitoring the entire earth. Landsat 3 launched in 1978, had a 75m resolution, and cost close to $1B in inflation adjusted dollars. By 2003, image chips had dropped to about 1 cent per sensor pixel. Landsat 8, launched in 2013, is capable of 15m resolution and cost $1B. Figure 9 represents the proliferation of commercial satellites now trackable through a google earth plug-in. By 2014, a convergence of the new "Internet of Things"(Ashton 2009) and open source software enabled un-manned aerial vehicles (UAVs) to produce aerial imagery of 5cm resolution, for a few hundred dollars (Devictor, Whittaker, and Beltrame 2010; Dickinson et al. 2012; Lane et al. 2010; Xiang and Tian 2011).

Figure 9 – The proliferation of commercial satellites illustrates an interim step(middle back quadrant) in increased resolution and frequency of earth observation in the trajectory illustrated in figure 8. The accessibility of the data generated by both these tools as well as consumer grade observation tools is illustrated by this screenshot, which was generated by the AGI(Agi.com) Google Earth Plugin that tracks real-time (updated every 30 seconds) positions of 13,000 satellites.

From a systems framework perspective, the scale and resolution of images and sensor data is relevant to the size and type of audience or social system. Global images and data patterns are relevant to billions of people, as illustrated with global climate modeling. Large scale models may affect cultural values, but may not be useful for daily management decisions at a sub-system field or watershed scale. The images and data from a single field at plant level or even leaf level analysis is most relevant to just a few people making management decisions, but does not reveal wider patterns across a landscape. However, *collaborative and networked data, including images gathered from fields across a landscape, have the potential to provide highly relevant environmental data patterns to billions of people, while engaging more people in a* *process providing the high spatial, spectral, and social resolution and feedback necessary for adaptive management.* The digital nature of observation technology that can be shared socially is crucial for collaborative adaptive management. Free tools, such as Google Earth, now enable management of all scales in a single intuitive interface leveraging collaborative computing, memory, and network power. The contemporary computer-generated representation of the Earth made possible by tools like Google Earth elevates environmental awareness through dramatic presentation of visualized data sets. However, it also reduces the representation of the Earth into an object that can be managed and manipulated. There is no assurance that the power of technology will direct efforts towards regeneration and away from extraction and disconnection from the natural world; hence, the importance of having a social framework (in the case of this study, Physiocracy) to encourage the underlying values that lean towards regeneration and resilience.

The challenge, therefore, is to leverage the existing system of highly inaccessible, centrally controlled, high cost, highly calibrated accuracy, as characterized by the NASA model of remote sensing, with the low accuracy (high resolution, but low calibration), low cost and low accessibility (socially and technically isolated tools) systems generated by the amateur-driven DIY, Hacker and Maker movements (C. Anderson 2012) into larger participatory systems bounded by the values of the Physiocratic model. The goal of expanding citizen science is also referenced as participatory action research or PAR (Joseph and Andrew 2008). Each transition identified is the byproduct of technical and social limitations, the relationships of which shift dynamically. Later chapters and Parts II and III examine the convergence of factors and applied examples as case-based studies that illustrate systems transition, and illustrate open source community approaches in action.

Validation of Low Cost Observation Technology

A low cost, networked, participatory approach does not replace conventional methods, but rather leverages the best contemporary conventional field and lab methods to validate and calibrate lower cost approaches made possible through reductions in technology costs. The marginal value of each field study increases, because each new validated data point also creates a parallel database that can then act as a calibration or validation library to reference using methods such as artificial neural networks. Validation of this type, achieved through data analysis and ground truthing, is required to achieve the promise of low cost and "light" systems on the front end - i.e., delivered back to handheld electronic devices that can *mimic or even improve* on the knowledge and expertise applied by an experienced field soil scientist, botanist, agronomist, or other specialist.

Aitkenhead (2013) created a practical application of this approach in Scotland and has published an automated methodology using the Scottish soil survey to visually detect soil properties. Aitkenhead has gone on to create a smartphone camera protocol that uses a calibration card and coordinates from the sample location to feed results back to the field. His approach relies on large databases and computationally intensive neural network processing, but enables a very light and distributed front end smart phone application. Without the validation from database libraries and associated processing power, the smartphone is not as useful to diagnose soil properties. It is the social and collaborative effort of populating the databases and creating the reference data that makes this tool useful. Collaborative social technologies, such as Microsoft's Photosync, demonstrate the future of interactive linked metadata that enable relationships to be built and value created through participation. The extension of this effect enables the user to change perspectives from zooming out to landscape level and down to the leaf level metadata. The technical achievements making this reality possible are outlined in Chapter 5, and the social systems that support it and build trust and legitimacy are discussed in Part II of the study.

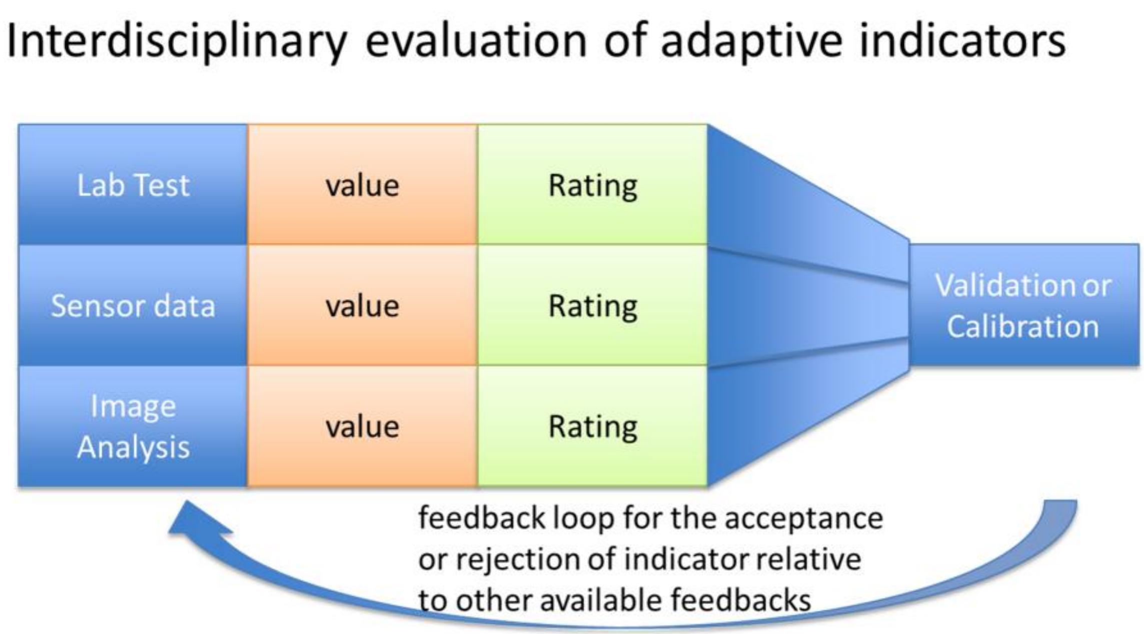

Figure 10 – A generalized adaptive management workflow for indicator evaluation. The development process illustrates a workflow that enables the evaluation of new indicators and data sources across data gathering and processing methods. Adaptive Management is based on constant feedback (Walker and Salt 2006). **A proliferation of data sources, many of which will not be calibrated or validated, also requires an approach to catalog and evaluate data sources towards improved systems function indicators. Values are the absolute measurements gathered, and ratings indicate a value added process that relates the measured values to moving benchmarks.**

Sustainable agriculture is particularly dependent on documentation because of the biological complexity that is relied on for nutrient cycling and other services. Variations in local soil and weather conditions are crucial to understanding claims of success or failure of any given practice, but especially in sustainable systems. The political power dynamics of sustainable agriculture also puts the burden of proof on sustainable producers to quantify positive environmental services, while the dominant agricultural system does not have to prove either benefit or lack of harm to soil, air, and water resources beyond following industry best management practices. The health and condition of soil can vary widely among farms based on past management, and previous treatments from trials on a given site may have variations in compaction, microbial activity, water capacity or other biological or physical characteristics. Such variability creates conditions impossible to replicate without detailed historical knowledge (Kimetu et al. 2008). Sustainable systems also add variables, such as increased rotation and greater soil life diversity that must be understood and incorporated for systems understanding and analysis. Accommodating this complexity requires observations of higher frequency and resolution, at lower cost. To be feasible, it requires an approach to research and data gathering methods that leverage the current state of technical knowledge and open source culture. *Wider access to tools at lower cost enables more questions to be asked, and more research completed by more people, more rapidly* (Couvet, Jiguet, Julliard, Levrel, & Teyssedre, 2008; Irwin, 2001) that might otherwise not be economically feasible in current research and development conditions (Pearce, 2012). The desired outcome of new approaches is greater understanding and participation of the population at large in sustainability science with the potential to make *every farm a research farm and every backyard a laboratory for continual feedback*. The cultural shift represented by this paradigm forms the basis for collaborative adaptive management to meet the challenge defined by the National Research Council to *assess and* *measure progress along a sustainability trajectory* and to build a systems framework to support those efforts.

Adaptive Cycle and Open Source Culture

Highly specialized, deductive approaches to research, knowledge, biology, and economics have resulted in substantial gains in understanding the biological and chemical mechanisms of our world as well as the manufacture of new materials and tools that now enable vast manipulation and observation of our environment at a global scale. Some academics have, controversially, labeled our geologic era Anthropocene (Age of Humans) (Walker and Salt 2006) to indicate our impact on the natural environment. Even the less disputed terms of “globalization” and “industrialization” denote the negative side of specialization that has created well-documented social, biological, and economic externalities on a global scale. Examples of negative externalities include imbalances in the carbon, nitrogen, phosphorus, and water cycle, decreased ecosystem resilience and diversity (Reganold, Jackson-Smith, and Batie 2011; Lal 2004), and increased economic inequality (Piketty 2014).

C.S. Holling’s concept of the adaptive cycle (Carpenter et al. 2001) was derived from the comparative study of the dynamics of ecosystems. It focuses attention beyond growth and conservation and onto the processes of release and reorganization. The adaptive cycle patterns also encompass general system dynamics, and have been applied to social and market behavior as well as ecosystems (Oelofse and Cabell 2012).

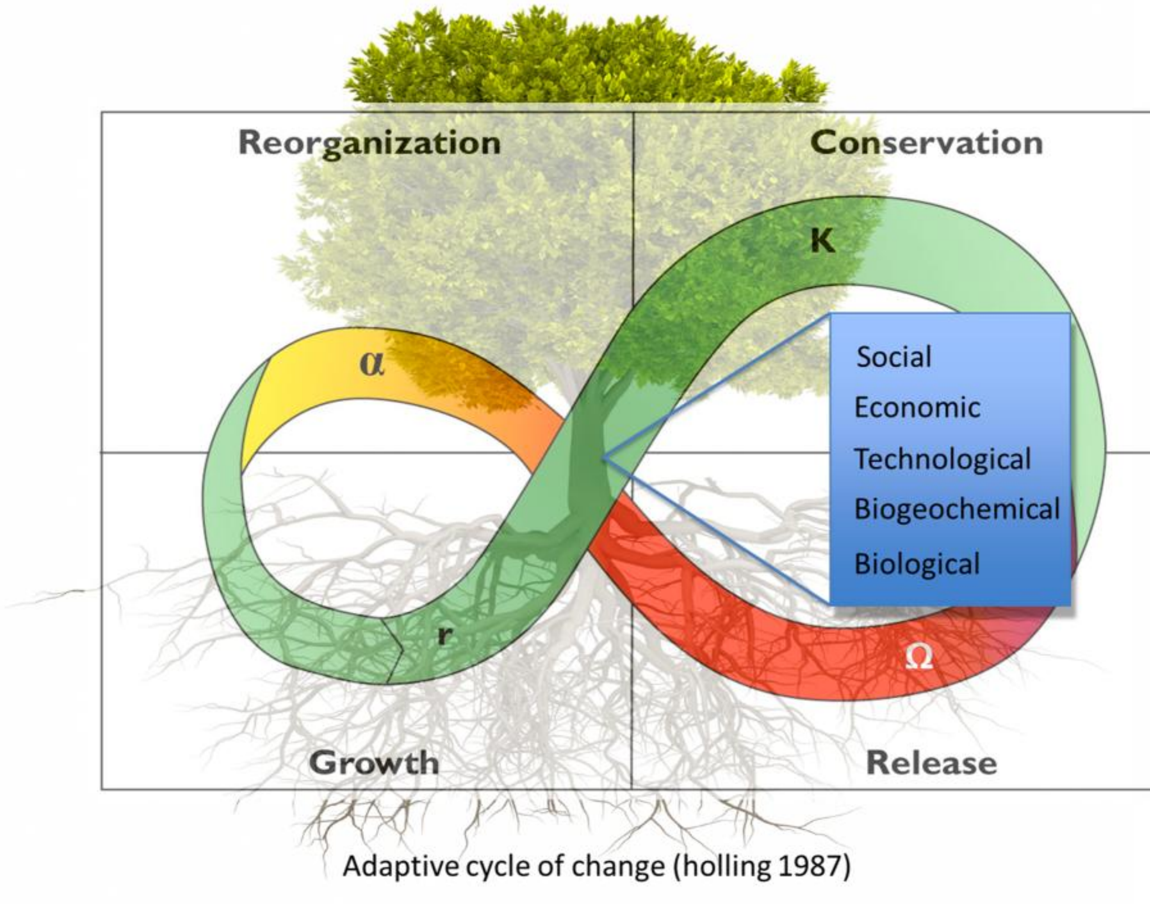

Figure 11 - The Adaptive Cycle of Change is encapsulated by Mirabeau's Tree metaphor. It can also incorporate social, economic, technological, biogeochemical and biological system dynamics. The adaptive cycle of change, illustrates the four generalized stages of systems change from growth to conservation, release and reorganization (Holling, Gunderson, and Ludwig 2002)**. It is useful within the Physiocratic framework of system behavior to identify relationships and leverage points within the system. For example, social and economic systems are resisting change in the late "K" conservation phase, while technology is in the "r" growth phase, and biogeochemical and biological systems are interacting in between "Ω" release phase and "α" reorganization phase. Mirabeau's Tree provides a method to bridge the mismatches and relate the abstract concept of the adaptive cycle to areas of human action and interaction within the interactions of these systems.**

The primary characteristics of the adaptive cycle phases are as follows:

- Most systems are not static; they are dynamic and change over time. While not entirely predictable, these changes often follow a pattern in which four phases of change are commonly observed.

• During the growth phase when resources are plentiful, fast-growing entities that can take advantage of these resources tend to dominate the system.

• As the system matures, it enters a conservation phase where resources become 'locked up' in longer-lived entities, (e.g., nutrients in the soil are absorbed by trees) and are no longer available for new colonizers. As a few species or organizations come to dominate in the conservation phase, the system tends to become less flexible which increases the likelihood of collapse.

• A release phase is often viewed as a disturbance to the system. Disturbances can destroy structure and other forms of capital, whether it is natural capital, such as accumulated biomass in a forest, or social capital such as policies or relationships, as suggested by the history of the telephone industry. These forms of capital have accumulated during the prior growth and conservation phases.

• The release phase is quickly followed by the reorganization phase during which new entities and innovations may enter the system but only a few will survive through to the start of the next growth phase.

• Often the new adaptive cycle will be very similar to the old; at other times, it will be very different. Forests may re-colonize with similar species and assemblages.

• The system needn't move sequentially between the four phases of the adaptive cycle; other transitions are possible. Nonetheless, these four phases seem to capture the behavior, structures, and characteristics of many systems.

• Sometimes, a release phase is beneficial at the local scale. It can invite innovation and provide a 'window of opportunity' for creating a new system configuration when the old one is untenable.("3.1 Cycles of Change: The Adaptive Cycle" 2014)

The current research and development environment is typical of the conservation phase of the adaptive cycle that resists change and tends to maintain the status quo.

Figure 11 illustrates the relationship of the K (conservation) phase within the adaptive cycle. The conservation phase is typified by protective behavior, declining cultural and environmental support, and a defense of the status quo. Monopoly behavior in industrial agriculture is exposed in patent protection of genetic material, large spending on government lobbying, price fixing suits, fights to prevent GMO labeling, and requests for "ag-gag" laws that make it illegal to document and publish photos from agribusiness facilities. These examples provide evidence of established interests' political and market power to maintain the status quo. In its current form, industrial agriculture is less a free market as idealized by Adam Smith than it is comparable to the granted monopoly-based mercantilist economic system of pre-revolutionary France that inspired the Physiocrats to call for "laissez-faire" ideals (Higgs 2001).

The political power dynamics in the conservation phase of the adaptive cycle lead to inevitable excesses, and contrasts with the reorganization phase where open source culture thrives. In this context, the Physiocratic, agrarian, and now open source communities have acted as balances to, and in reaction to, established interests and power structures. Open source and sustainable agricultural interests are still a small market relative to total cultural presence, but agricultural legislation and market growth are now being driven by values established from perspectives beyond commodity production. The growth of process certifications such as organic, humane, gluten- and GMO- free are all indicators of this cultural process in action.

Open source communities are generally established with the expectation and benefit of rapid innovation and adaptation, tendencies that are aligned with the release and reorganization phases of the adaptive cycle. The language of self-identified "communities" itself is indicative of sociopolitical self-awareness. Counter-culture and populist values are well known aspects of the most successful open source software projects such as Linux, Apache, and Mozilla (Hertel, Niedner, and Herrmann 2003) which attempt to operate outside the patent system. A similar cultural approach and strategy extended beyond software and gained national attention in June 2014, when the electric car company, Tesla, announced that it would not defend any of its hundreds of patents but would instead focus efforts on innovation. Shifting the strategy from short term extraction in the form of protection of intellectual property to long term innovation and adaptation illustrates a cooperative approach in response to the hegemony of established interests. Tesla CEO Elon Musk in a 6/17/2014 MSNBC interview put the decision in context:

> "Say there are a bunch of people on a ship and a bunch of holes (are in) the ship, we are quite good at bailing water out of our section and have this nice bucket. We are foolish not to share that nice bucket design because if that ship goes down, we are going with it"("Elon Musk Talks Tesla and Climate Change | MSNBC" 2014).

The analogy also fits tightly within Herman Daly's Plymsoll line carrying capacity metaphor (Herman E Daly 2007), that a heavily laden ship is more vulnerable in a storm. In the context of the adaptive cycle, these metaphors describe the conditions required for resilience in the process of shifting from the conservation phase to reorganization.

Agile Development and Adaptive Management in Research

In many ways, open source hardware and software development methodology parallels natural resource management adaptive management systems approaches.

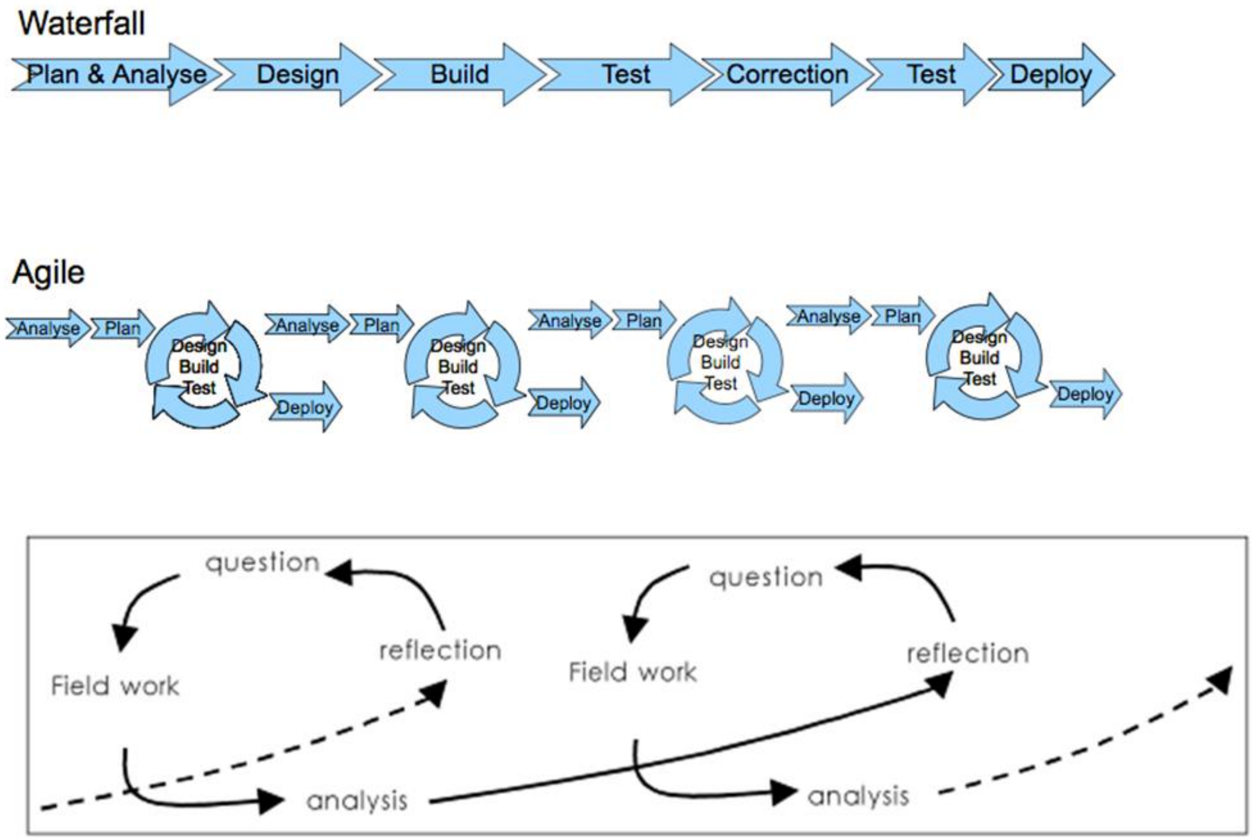

Figure 12 - Agile software development process as an analog and precursor to adaptive management. The Agile Software development process is an iterative process that does not prescribe outcomes, but is driven by constant evaluation and correction that enable adaptation. The Agile process is presented in contrast to waterfall development methodology that is less collaborative and based on more fixed roles and responsibility within a team. There is a marked similarity to the spiraling questioning characteristic of adaptive management as illustrated (Probst and Hagmann 2003)**. The parallel culture of adaptive management and agile software development methods and tools is significant because future developments in cultural practices and adoption of collaborative adaptive management will be codified in software workflows.**

Both systems operate in contrast to more rigid approaches. In the case of open source software, Agile development (horizontal, with constant feedback loops) is used in contrast to management driven Waterfall type project management (top down, with limited feedback loops). Agile production, best known in corporate circles as the "Toyota production method," is characterized as being horizontally developed by smaller semi-autonomous distributed teams that create and test quickly and collaborate actively across a network. In natural resource management, the Waterfall approach is illustrated by the rigid "best practices" model of governance developed through a hypothetical, deductive approach dependent on following prescribed steps. There is a growing set of voices critical of the traditional version of this method (Bauer 1992; McComas 1996; Lederman 1998; Giunta 2001).

Agile development describes a more iterative and adaptive approach to software development more aligned with an adaptive management approach in agriculture. Large companies such as IBM have embraced and popularized both Agile and open source approaches, while the "waterfall" approach has fallen out of favor. Figure 12 illustrates the contrasting methodologies and how they relate to emergence and iteration. There are benefits and clear challenges articulated throughout this study in creating a research process that is itself adaptive and that focuses on uncertainty. Embracing emergence and uncertainty also enables constant improvement and evolution in the questions that can be asked.

Science at its essence is a process of discovering order in the natural world, and using that knowledge to describe what is likely to happen in nature. Important outcomes of science are principles that explain what consistently happens in nature; however, there are many ways to approach and test systems (Miller, 2005). The social consequences of an overreliance on deductive methods and the positive implications of revaluing exploratory, inductive methods of agricultural research are drivers for this study's analysis. Agricultural systems represent a particular challenge to the hypothetical, deductive (Waterfall) model, because of the number of uncontrollable variables and complex interactions, especially when studied at a landscape and watershed level. A more inductive, adaptive (Agile) approach enables the flexibility to follow unanticipated results by observing and then adjusting the research questions in response to unforeseen variables as they are inevitably encountered. The Physiocratic social framework outlined in this dissertation provides a context for participatory research approaches that flourished during the Enlightenment period when no theory had yet been established; the approach was quashed with the rise of industrialism, professional science as a field of expertise, and an emphasis on deductive methods. Agile, adaptive management approaches offer a resurgence of the potential to foster curiosity and participation in the broader population, and to develop effective tools for the documentation of soil, plant, and management interactions across a landscape. The social structure of Agile, open source development is flat, and enables input to come from any source. It puts tools in the hands of those who are willing to question and take action. The social structure of the method creates both a social benefit and a communications efficiency gain that is inherent in the process. The concept of *iterative inquiry and action* is central to the promise of open source agricultural research and development.

Adaptive inquiry more closely represents the informal process that producers go through on the farm every day, and can become a pathway into a larger inquiry. While previously too expensive to allow a systems approach beyond the individual field, this method can now be coupled with newly inexpensive, statistical and observational data logging tools to enable a "blanket approach" to document as many indicators as possible to explore the results retroactively. This neutral data collection method of filling extensive "Baconian Tables" (in reference to Sir Frances Bacon's description of the inductive process) creates a model for inquiry that does not put the burden of experimental design on accurately foreseeing the expected results, but rather creates opportunity for involvement, rigorous scientific inquiry, and adaptive feedback loops regardless of the variables (Harwood 2004).

A more cyclical, adaptive approach to inquiry challenges some of the basic industrial, cultural structures that are embodied in the reward systems and funding mechanisms for research. Part of the requirement for adaptive management and the creation of Agile research teams is a more horizontal and participatory structure. Agile research is less management-driven, can take input from multiple sources and types, and enables multiple interpretations and explorations of the data. In contrast, the conventional deductive research model is more product than outcome based, focusing on certainty rather than uncertainty. Because it relies on building blocks of only known knowledge, it also limits participation to experts in their domain to assemble those blocks of knowledge together. In essence, the deductive approach is a reflection of the consumer based socio-economic model that creates two classes of participants. The byproduct of this approach is the cultural perception that innovation happens only through special people (scientists, inventors, etc.) working in special places (Laboratories, R&D centers). This construct carries through beyond manufactured goods, to non-rival goods such as media and scientific knowledge (Michael 1998), and creates a consumer model of passive dependence on the "producers" of products and knowledge. In contrast, the Physiocratic framework for an open source, inductive process reopens the process of inquiry to the commons, viewing the creation of shared knowledge and involvement in natural resource decisions as a public good and a civic obligation. Rather than dependent consumers, participants in this framework can become an empowered and active part of the improvement and development of products, and even the manufacturing process. Open source development using Agile methods and related methodologies, such as Collaborative Adaptive Management, close the artificial gap between "producer" and "consumer" through a structure and development process that is unified, horizontal, and requires participant engagement and decision making to be successful.

Measuring the Commons to Reduce Externalities

The emerging open source agrarianism echoes the ideals of social justice concepts of self-determination that emerged during the Age of Enlightenment. John Locke's 1690 Second Treatise on Civil Government stated that (emphasis added):

> "Though the earth and all inferior creatures be common to all men, yet every man has a 'property' in his own 'person.' This nobody has any right to but himself. The 'labour' of his body and the 'work' of his hands, we may say, are properly his. Whatsoever, then, he removes out of the state that Nature hath provided and left it in, he hath mixed his labour with it, and joined to it something that is his own, and thereby makes it his property. It being by him removed from the common state Nature placed it in, it hath by this labour something annexed to it that excludes the common right of other men. For this "labour" being the unquestionable property of the labourer, no man but he can have a right to what that is once joined to, ***at least where there is enough, and as good left in common for others***" (Locke 1952).

Locke's statement highlights many common elements in the current dialogue about sustainable agriculture. He identifies the fundamental economic equation of agriculture and the concept of property ownership and stewardship by direct action and improvement, and its relationship to the commons and related ecosystem services. He holds that Nature and land are common, that the improvement from the product of labor is due to the laborer, up until there is not enough in the commons for others. The last sentence – "where there is enough, and as good left in common for others" is often overlooked in favor of the industrialist's expedient reading in favor of extractive property rights. Disruptions in the provision of nature's benefits caused by human action were already recorded in ancient civilizations by Plato's descriptions of the effects of deforestation on soil erosion and the drying of springs in 400 BC (Daily, Matson, and Vitousek 1997; Gómez-Baggethun et al. 2010). The pace of technology to monitor human changes to the biosphere has lagged behind the pace of industrially extractive technologies, which were enabled by capital and hired labor to change our environment, at a pace beyond Locke's comprehension. It is a perversion of Locke's logic to treat this mechanical pace and hired extraction with the labor of an individual for his own use and improvement.

There is a deep concept of justice in the idea of the commons in nature that is a constant theme of human history and is now echoing globally in the context of climate change dialogues and local food movements. Jonathan Swift famously wrote that

"whoever could make two ears of corn or two blades of grass to grow upon a spot of ground where only one grew before, would deserve better of mankind and do more essential service to his country than the whole race of politicians put together" (Swift 1726).

Swift's statement also emphasizes the economic equation of sustainable agriculture, and the social and biological values associated with it. These social echoes are currently relevant because they are being employed in contemporary settings and represent an underlying shift in social values which in turn forms the basis for sustainable agriculture and the understanding of ecosystem services within popular culture.

Substitutability arguments which came out of neoclassical economics identified capital as the primary limiting factor, even for ecosystem services (Gómez-Baggethun et al. 2010). However, there is an emerging understanding that good management and maintenance of ecosystems can function and provide the same services more economically than built and capital infrastructure. Post-disaster planning conducted after environmental crises such as Hurricanes Irene and Katrina has increased the public awareness in the United States that there is a much lower cost in managing ecosystem services like salt marshes, mangrove swamps, seagrasses and similar natural buffers, than substituting the function with built capital of concrete and steel. The blueprints for lower cost solutions already exist in nature (Benyus 2002). As Antoine de Saint-Exupery explained, "You know you've achieved perfection in design, not when you have nothing more to add, but when you have nothing more to take away" (Saint-Exupery 1939). From the dust bowl to more frequent flooding, drought, and more severe hurricanes predicted by climate models, cultural insights in valuing ecosystem services move from theory to economic reality and become part of the public planning process.

The conventional economic model has enabled cultural and economic values that do not provide for the fundamental difference in the *nature* of agriculture, in its broadest sense, from all other human enterprises, and the fundamental biological relationship to improving or degrading ecosystem services. By devaluing the importance of agriculture and by not having sufficient feedback mechanisms, the result is an economic model as illustrated in figure 13, with a small root system supported by external inputs and without a resilient base of deep roots. In nature, trees expand their root structure as their canopy grows. A tree with a large canopy and small roots is inherently unstable and vulnerable to stresses. It is more easily blown over.

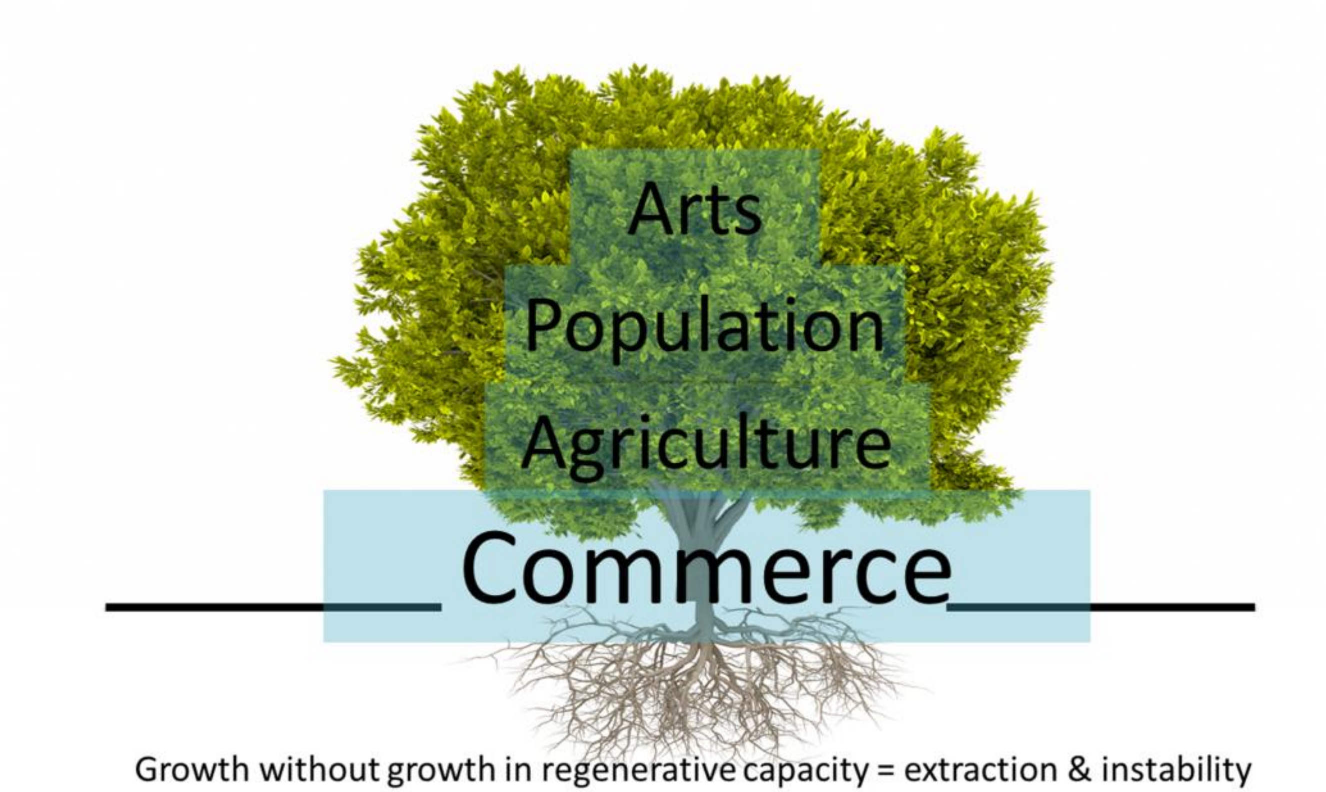

Figure 13 – Mirabeau's tree represents the reduced resilience of a commerce driven system. The inversion of agriculture as a subset of commerce, rather than commerce as a subset of agriculture, illustrates the limits to growth of the contemporary economic model. The externalities are evident in undervalued contributions of land improvement and the capacity for regeneration expressed as a small root system and a large canopy. The result is a system dependent upon extractive growth rates explored in limits to growth theories (D.H Meadows et al. 1972)**, one that is top heavy, vulnerable and unstable.**

Climate change models bear this metaphor out: we see cities around the world which have neither planned for nor taken this vulnerability into account facing more severe weather and rising seas. Cultural systems and environmental feedbacks lag behind the ability to extract and change the global environment, in part because culture and evolution are sequential and cannot re-combine out of order. Technology, on the other hand, is not limited to a single generation's genetics and is therefore unbounded by linear sequencing; it can grab genetics from across "species", even "extinct" species, as long as there is documentation (in this metaphor, DNA) (Kelly 2010). Author Kevin Kelly refers to almost life-like evolution of technology as the "technium." The technium he describes emerges from environmental conditions and has parallel traits of convergent and co-evolution. It has characteristics of a "selfish gene" (Dawkins 1976) and expresses the power of accumulated knowledge and also the danger, the mismatch between the pace of technological evolution and cultural assimilation. The slow feedback results in a lag time between technical achievements and incorporation of skills and cultural values that internalize the technological implications, especially evident in the documentation of complex systems found in the natural world. This phenomenon is observed in the environmental externalities of industrialization that were created before they could be measured.

However, the Physiocratic living metaphor is bounded by what can be **grown** through stewardship, and so **total growth is limited to actual regenerative growth** provided by root structure and stewardship of a natural system; in other words, what regenerative agriculture can support in terms of food, fuel, and raw materials. The industrialization of agriculture enabled a rapid bypassing of this slower, but more stable, and realistic concept of growth that incorporates feedback for cultural assimilation. The result of bypassing this equation was rapid, but unbalanced, industrial economic growth, without the technical tools to evaluate the change, or time enough for the feedback required for social values to catch up. The result is the contemporary unbalanced biogeochemical and social systems we have today.

The industrialization of agriculture created economic models that both blurred and ignored the distinctions among agriculture, mining, and manufacturing (Gómez-Baggethun et al. 2010). In the broad sense, agriculture and mining are the most fundamental ways in which humans interact with our environment, while manufacturing transforms the raw goods either grown or extracted from the other two. The blurring and obfuscation of these fundamentally different relationships is reflected in economic and popular literature (Gómez-Baggethun et al. 2010). In the latter half of the 20th and beginning of the 21st century, agricultural economics was reduced to its factors of production, which fails to recognize the fundamental difference between agriculture and manufacturing as identified within the structure of Mirabeau's tree.

The result is an imbalance between the regenerative capacity of the natural systems and the population, commerce, and arts sustained by it. Figure 15 illustrates this imbalance by showing a shrunken root system supporting a large canopy of commerce, expressed as pollution, land use, and ownership patterns. Applied examples covered in later chapters focus on the particularly top heavy nature of the New England economy, which produces only a small fraction of its own food and energy (Timmons 2006; White 2014). The tree metaphor shows that the tree/culture might survive in good conditions, but without deep roots would not be resilient to storms, drought, or other stresses. In this way, the metaphor also functions in a similar capacity to Daly's earlier mentioned Plimsoll line metaphor for the Earth's carrying capacity. The ship metaphor illustrates resilience in terms of the inherent vulnerability of an overladen vessel to adverse weather conditions (H. E. Daly and Townsend 1996). The difference is that Daly's metaphor doesn't allow for the growing of a bigger or more stable boat through management of natural systems!

Cultural Values and Internalization of Ecosystem Services

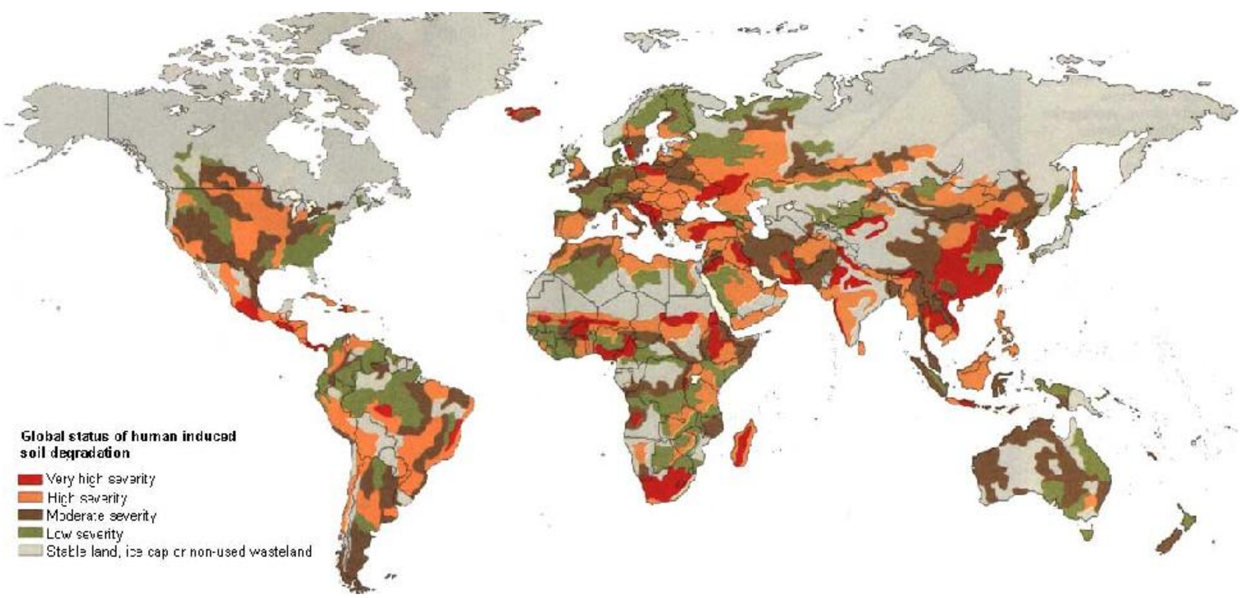

Figure 14 –Market failure expressed as human-induced global soil degradation (FAO 2014). **This image illustrates the outcome of Figure 13 as an extreme example of market failure caused by inaccurate indicators caused by a commerce rather than agricultural driven system and slow corrective feedback loops that enabled the temporary ability to ignore agriculture as the basis for civilization. The result was market values that have failed to account for the degradation of the commons in the form of regenerative soil and water resources.**

The shift in the language of land, soil, and the subsequent treatment of factors of production shows how important environmental feedback and connections are to creating cultural values around ecosystem services. Cultural values directly relate to the framework and feedback mechanism, and inform how a population interprets its own environment. Just as European settlers' observations of the perceived abundance of the New World was informed by the Old World's perceived scarcity (Cronon 1983), so do industrial hegemonic values influence contemporary values placed on land and the care of land (Levy 2005). Global soil degradation and soil health, illustrated in figure 16, are the most dramatic examples of environmental indicators ignored or simply thought irrelevant by economic schools of thought (David a. Robinson and Lebron 2010; D. Robinson et al. 2013). The climatic and ecosystem service degradation caused by this oversimplification illustrates the consequence of inadequate environmental feedback loops and of cultural systems that have isolated people from nature (Walker and Salt 2006). Chemical soil testing performed to the exclusion of a holistic approach is a well known example of how the industrial system of specialization led to unintended external costs of degraded soil (Idowu et al. 2009). In this extreme case, it has led to cultural values that lack feedback to appreciate and maintain soil and nutrient systems as the most basic building blocks of civilization (Wrench 1940; F. H. King 1911; Ohlson 2014).

Figure 17 illustrates the feedback process that leads to greater soil degradation. If systems feedback, like reduced water capacity or increased compaction, is recognized and valued, management changes and actions can stop the downward spiral. But if soil is not managed as a complex system but instead a simple input/ output factor of production, then the feedback is inadequate and even detrimental, resulting in a reinforcing pattern of degradation.

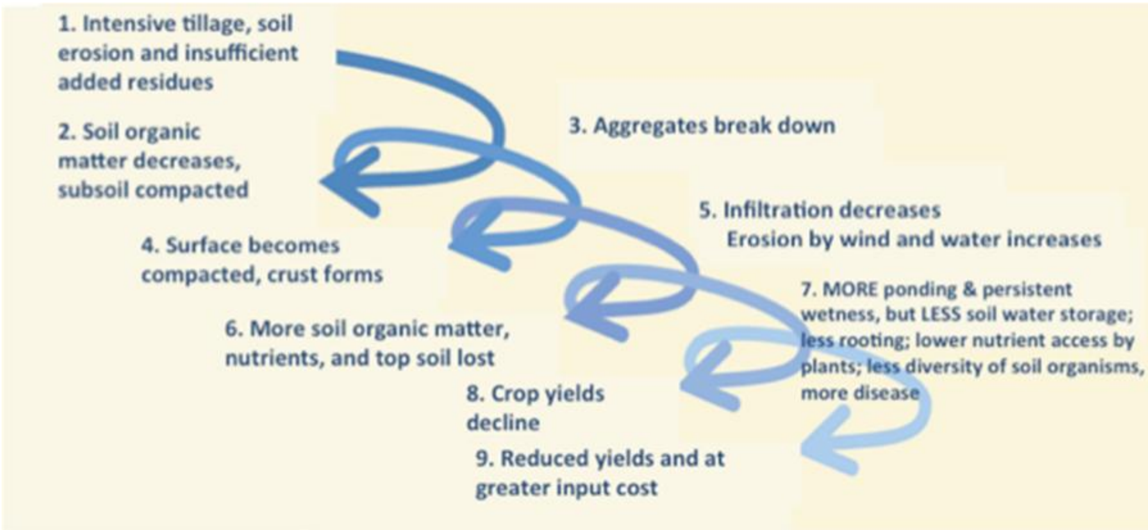

Figure 15 – The soil degradation cycle (Magdoff 2000) **illustrates the negative feedback loop of management attempts to compensate for a degraded resource without adequate feedback about the biological functions of soil. The reversibility of this cycle is central to the Physiocratic framework. The sdiagram frames the exploration of observational and analytic tools to provide the feedback necessary to farmers and managers to document and reverse the degradation process illustrated in Figure 14.**

Soil Health, Resilience, and Optimism

The history of soil degradation and the promise of soil regeneration has been captured in agrarian literature in books such as *Farmers of Forty Centuries: Organic Farming in China, and Korea* first published in1909, *Reconstruction by way of the Soil*, published in 1940 and more recently in books listed as Amazon.com's top agricultural reads, including *The Soil Will Save Us: How Scientists, Farmers, and Foodies Are Healing the Soil to Save the Planet* published in 2014 and *Grass*, *Soil*, *Hope: A Journey Through Carbon Country*. The content of this study is referenced throughout *Grass, Soil, Hope* (White 2014).

A theme of the above books, in the agrarian tradition, is a sense of optimism and hope that through personal action, management can have a positive effect on natural systems. There is also emerging communications literature on this particular aspect of environmental communication strategy (Bolderdijk et al. 2012). The Common Cause for Nature, a group of environmental organizations, released a report stating that,

> "Provoking feelings of threat, fear or loss may successfully raise the profile of an issue," but "these feelings may leave people feeling helpless and increasingly demotivated, or even inclined to actively avoid the issue". People respond to feelings of insecurity 'by attempting to exert control elsewhere, or retreating into materialistic comforts.'

The common sense of optimism and empowerment shared by agrarian, Physiocratic and Open Source narrative place the individual within a context that is empowered to create more stability and security rather than fear and powerlessness. This is in contrast to communication from the consumer based memes such as "peak oil," and "carbon footprint," which leave the citizen in a helpless role, dependent on "producers" to change, or to only to be able to change "consumption" patterns, within the confines of the existing regimen. Building resilience through soil health, and measuring and including every citizen within that dialog, is part of a communications strategy that the agrarian themed books embrace, and is a consistent element in Physiocracy. The sociology of resilience in cultural patterns is clearly tied within the concept of soil health and its management as presented by the above authors.

Fortunately, the soil degradation cycle is reversible and the inverse of the same factors that degrade soil can both increase soil health and resilience and help balance the atmospheric surplus. Health is a systems concept, and therefore there are many ways of measuring it. The most basic definition of soil health is the capacity of soil to function biologically, chemically, and physically. The Cornell Soil Health test started with 96 indicators to measure health, and has worked down to the thirteen indicators for the 2013 test. Iteration and refinement is a constant process and, as part of that maturity, the Cornell Soil Health test has become part of a national collaborative effort to refine and standardize soil health indicators. The physical indicators include aggregate stability, water capacity surface compaction and sub-surface compaction. The biological indicators include organic matter, active carbon, respiration, ACE soil protein index, and root pathogen pressure. The chemical indicators include the standard pH, P, K and micronutrients.

The Soil Renaissance project, initiated and funded by the Noble Foundation and the Farm Foundation, has advisory members from national conservation groups, government officials, and scientists coordinating an effort to standardize Soil Health indicators. The existence of the Soil Renaissance project is culturally significant because the source of the funding and the "conventional agricultural" stakeholders involved. It is as an indicator of a broader cultural engagement with environmental service values associated with agricultural management. It is also an illustration of the potential practical application for the immediate expansion of the collaborative adaptive management framework identified by this study.

Soil health is a management variable that can add resilience to systems by mitigating environmental and management variations, especially in drought and flood conditions. Resilience is an especially important economic concept in relationship to soil health because of the vulnerability of agriculture to volatility and variation, not just from weather but from other cycles, such as bird migrations, insect life cycles and pathogens. Resilience is defined as the capacity to recover from perturbation and disturbances, while retaining structure function, identity and feedbacks (Brand and Jax 2007; Holling et al. 2002; Lal 1997; Walker et al. 2004, 2010; Walker and Salt 2006). A soil with low resilience can degrade beyond a critical threshold because of alterations in key soil properties and processes. For example, decline in soil depth by accelerated erosion, or a decrease in Soil Organic Content, can drastically alter soil health with the adverse impacts on agronomic production and other ecosystem services (D. E. Allen et al. 2011).

Resilience and transformability are essential attributes of a good soil health. In the context of changing climate and other perturbations, building soil health is essential to coping with external changes and meeting the growing demands of increasing world population. Soils of good health with high organic matter concentrations have favorable physical, chemical, and biological properties and processes. Defining threshold levels of key soil properties specific to land uses and ecosystems is essential to managing and enhancing soil health (Lal, 1997).

The optimistic scenario represented in figure 16 has positive feedback loops based on increased soil health. However, to achieve the positive feedback results illustrated in figure 16 requires cultural shifts that treat soil as a complex social and biological system rather than something limited to geology and extractable minerals.

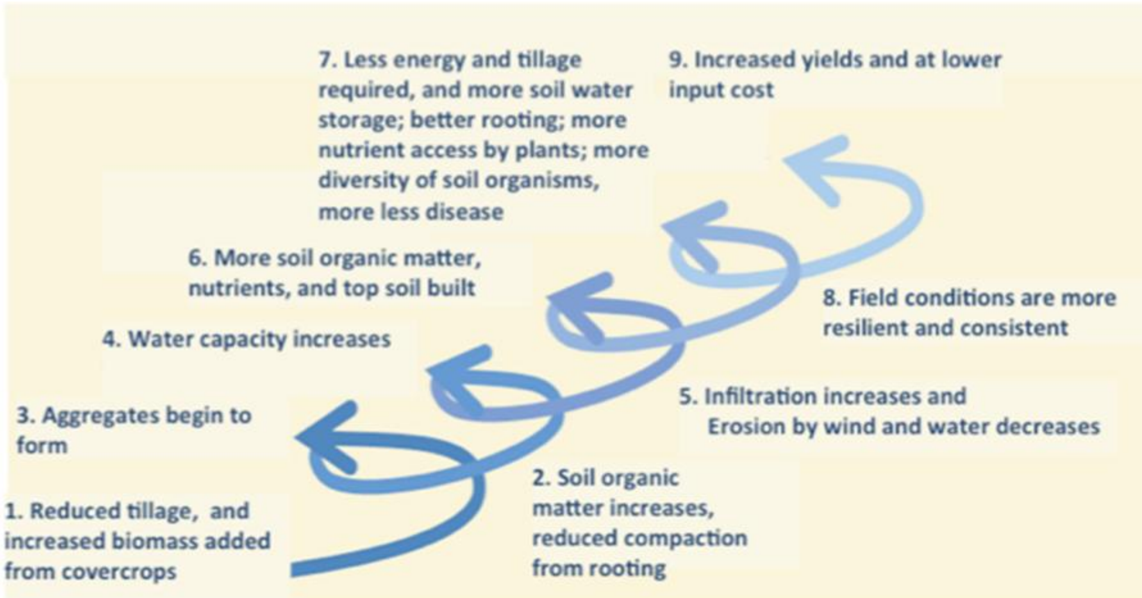

Figure 16 – Positive feedback loops of soil health and increased organic matter. The ability of farmers to improve soil with management is a central tenant of the Physiocratic framework. The pace and capacity for soil building has been underestimated, but the knowledge and tools to do so have yet to be widely adopted or prioritized as development strategies (United Nations Affairs Department of Economic and Social Affairs 2012)**. One indicator of a move towards changing this trend in the United States is the creation of the Division of Soil Health within the USDA/NRCS.**

Methods that produce quantifiable feedback and cultural support are critical to change behavior over time (Lal 2004). Recent technical achievements, such as soil imaging processed by neural networks to provide near real time feedback equivalent to an experienced field scientist, are part of the answer. But the cultural context and how the achievements are further developed, distributed, and used will decide if they will also shift wider cultural values and the perceived value of ecosystem functions to include public awareness of their own role within the water, carbon, nitrogen and phosphorus cycles. The simple figure of Mirabeau's Tree incorporates the concept of soil regeneration, with a sense of place within the larger system that is important both culturally and rhetorically to complement communications of optimism and empowerment through involvement.

The accounting process of measuring the positive change in soil, observable in just a single season, can be culturally powerful. Jethro Tull observed the same pattern over 250 years ago as recorded in the entry on Agriculture within the *Encyclopédie*: "This skillful academician wisely judged that one small example would have more impact than reasonings which, though sound, would not be understood by most men or trusted by those who might have difficulty in following them (Diderot 1751)."

In this feedback cycle, the deposits of surplus organic material feed into the "carbon bank." Once in the bank, the carbon deposits show a form of compound interest, creating a real return on investment. As one seed is invested and perhaps one hundred are returned back, biomass is returned as residue, and a season's share of nutrients that were pulled from the atmosphere and soil are circulated like blood through a body, a metaphor used by Quesnay. The soil responds, like a runner with a higher metabolism, like a muscle being used. When one seed is invested the following season, and one hundred twenty seeds are returned, a true compound interest based on the universal asset of life, carbon, is experienced, indicating an increase in return. The surplus added back to the soil has been truly earned, and has not been simply extracted from the millions of lives before us (White, 2014). This powerful process already observed during the Age of Enlightenment and formed the basis of Physiocracy.

Soil Health Measurement and Management

A dominant discourse in environmental economics often involves some variation of I = PAT, developed in the 1970s during the course of a debate between Barry Commoner, Paul R. Ehrlich and John Holdren (Ehrlich and Holdren 1971). They argued that Human Impact (I) on the environment equals the product of P= Population, A= Affluence, T= Technology. The formula indicates how growing population, affluence, and technology contribute to environmental impact. However, the framers of this equation and those to use variations of it since, have not articulated that human "impact" could be restorative and reactive, or could enhance diversity and ecosystem services (Palm et al. 2007) as figure 18 illustrates. Their prejudice is still seen in the framing of popular terms like "carbon footprint" and USDA tools with names like "Revised Universal Soil Loss Index" that assume human interaction with natural resources will inevitably result in some form of degradation without the potential for improved function of the biosphere. There is a danger in using history to model human behavior and the environment. It is like predicting the outcome of a sports game based on team records from ten years earlier: the teams have the same names, but the players are different. Just as there are environmental thresholds as described by resilience thinking, social thresholds also exist, which can result in new cultural regimes. The cultural effects of satellite images are an example, and global networked communications coupled with open source hacker culture may be another. The relatively recent shift within the USDA to emphasize soil health at a national level, a growing cultural acceptance of terms like soil health and all that it implies, and the many conventional funders fully embracing such approaches through efforts like the Soil Renaissance, indicate that past behavior by established interests can shift significantly and does not always predict future performance.

Jean Louis Comolli argued that the impacts of Renaissance perspective in terms of its effect upon scientific and industrial structures was both a cause and a consequence of a shift to a more humanist social regime (Gurevitch 2014). Measuring soil health and the human effect on it, and the Physiocratic belief that soil health *can* be managed and improved, follows this clear legacy. The use of Google Earth and similar levels of mapping further illustrates this point. Computer automation, and even animation of perspective and rendering, has far-reaching consequences for the relationships we have with representations of Earth, its ecology, and our cultural responses to externalities and climate change. This structured process of observation and action was formed from the renaissance perspective and created the active relationship between the Earth and humans which has led to the Anthropocene. Our ability to observe and generate human renderings of the Earth continues to evolve and contribute to the industrialization and science (Gurevitch 2014). The Physiocratic framework builds on the renaissance impulse of modeling and measuring our environment, but adds explicit values of improving soil health as social amendment to an earlier concept of the Anthropocene.

Chapter 4: Technology, Open Source Culture, and Participatory Research

Introduction

The contemporary focus on sustainable agriculture and natural resource management does not imply large-scale transfer of finished technologies, as has been the mode for a long time. Rather, it involves location-specific, informed practice, consensual decision making, and adaptive management. Implementing all these requires collective learning by farmers about technological and other innovations, and flexible options that can be adapted; enhancement of capacities for opportunity identification, problem solving, and decision making; platform building for resource use negotiation; and collective decision-making at the larger ecosystem level (Roling and Jiggins 1998; A. R. Braun and van de Fliert 2000; van de Fliert and Braun 2002)

A dramatic reduction in the cost of technological tools has resulted in a convergence of conditions that will alter who can observe, access, and communicate knowledge and alter social systems. The same computing power that now data mines Facebook, Google or Twitter for behavior patterns, or recognizes faces from snapshots, creates Instagram photos and shares digital self-portraits across the internet, can without any further technical achievement identify plant growth patterns, and map and rank environmental health indicators across a landscape. The annual report of the International Telecommunication Union (ITU) estimated that by the end of 2013, there would be some 6.8 billion mobile-cellular subscriptions – almost as many as there are people on the planet.

In 2000, 7% of the global population was connected to the internet; in 2014, the connected population was 40% (Meeker and Wu 2013).

However, the popular global industrial narrative has focused on the primary applications of technology as consumer uses or abuses. The demand for everyday consumer conveniences has become the primary market driver for the low cost gyroscopes, accelerometers, GPS, imaging chips, and memory now used in smartphones. The focus on monitoring the behavior of *people* and delivering the most common *wants of consumer culture*, misses the far more significant and consequential application of the same tools (Lane et al. 2010). These observational tools have the powerful potential to monitor the management of natural systems and dramatically involve a wider population in an open process of scientific inquiry by lowering the costs and risks of participation. Weather prediction is the most basic example of a distributed predictive modeling service provided to the general population. However, this example does not yet use private mobile devices to exchange and give dynamic feedback with those models. The technical capacity to achieve global distribution of the networked devices is already proven; the potential for participation and interaction through use of these tools applied to nutrient cycles is the topic of this study's socio-technical systems approach.

A number of different mobile phone applications (apps) are becoming available for environmental monitoring (Donnelly, Coull, & Black, n.d.; M. J. Aitkenhead, Coull, Towers, Hudson, & Black, 2012). Such apps fall into two different categories: observation recording and data access. The manner in which each app operates is different, as is the data that is either recorded or accessed by the user. Examples of “observation” apps include species identification and water quality monitoring. Apps of this type require a certain level of knowledge on the part of the user in order to produce reliable observation data. Monitoring equipment must often be used, for example pH or moisture meters, which can provide measurements that the mobile phone is not equipped to take. Another type of app that allows users to record their own information is the ‘mapping’ app, which can enable land managers, for example, to record the positions at which samples have been taken for later analysis. This type of app is useful for recording and retrieving the spatial distribution of observation points in relation to fields or other landscape features. However, it still requires the user to carry out additional (often costly and time-consuming) analysis. There are also apps that process user observations and provide decision support for agricultural and environmental management, for example in crop pest monitoring, crop yield prediction and farm management (M. Aitkenhead et al. 2014).

Examples of apps that allow the user to access existing data include interfaces for soil maps (e.g., Web Soil Survey) and more general environmental map information (e.g., Google Earth). These apps use the GPS function of the phone to pass the user’s location to a server where the map is stored; this information is then passed back to the user. The value of this kind of app is that it can supply the user with existing information, usually for free, that is from a reliable source. However, the observations that have been recorded do not always match those that are required by the user, and even if they do, they may be several years old. For some applications this is not an issue, but as mentioned above, some soil and landscape characteristics, for example land cover or soil moisture content, can change rapidly (M. Aitkenhead et al. 2014).

Beyond Smartphones and Networked Remote Sensing

Smart phones are a singular combination of technology oriented towards a particular use. Phones are generally tied to individuals, with not more than one phone per individual, which caps the potential nodes to about 8 billion devices. The "Internet of Things", or the networking of objects communicating about their environment, is not limited in any way to the number of people or their location. The Weightless company (http://www.weightless.org/) projects selling a network connectivity on a chip for under $2 that would last for 10 years on a single battery and communicate over 5km, which opens ethical and social considerations, but also illustrates the potential applications beyond smart phones.

For example, the World Wildlife Foundation is working with Conservation Drones (http://conservationdrones.org/) to put low cost Unmanned Aerial Vehicles (UAVs) in the hands of citizens to map watersheds, document habitat, and track animals and poachers (Koh and Wich 2012). Other applications, such as low cost wireless sensors that communicate independently but are also internet accessible, are proliferating (O'Flynn et al. 2007). IBM and Libelium partnered to create an environmental monitoring network in Lake George in upstate New York; a September 2013 Forbes magazine article profiled this effort with the headline "*Saving Lake George: Can Sensors and Big Data Protect $1 Billion In Tourism*?" Libelium's website continues the theme: "If we can harvest the Big Data insights from all of the things connected to the Internet we can more precisely understand how our world actually works." The development of techno-environmental optimism is highly reminiscent of the Physiocratic worldview that natural systems can be understood and governed, but also diverges from the alarmist rhetoric typical of the environmental movement of the past 30 years.

Open source research and development organizations such as The Public Laboratory for Open Technology and Science (Public Lab) and Farm Hack which are both discussed as case based studies in Part II of this dissertation, apply and illustrate this techno-optimism though cooperatively held events at the author's farm in Lee, New Hampshire, on a weekend in May during the years of 2012-14 called iFARM (Imaging for Agricultural Research and Management). Several examples of open source environmental monitoring hardware and software were presented that illustrate the social and technological convergences. These systems were all similar in approach, cost and structure to the soil imaging system already discussed. Examples of the open source community driven projects that illustrate technological approaches to environmental understanding included:

- RIFFLE - A < $100 water sensor (temperature, pressure and conductivity) data logger that can be housed in a water bottle enclosure. The Riffle is a Public Lab and Open Water project.

- FIDO - A < $100 wireless networked wifi cellular data logger with web interface and automation potential. FIDO is a Farm Hack project funded by KIVA and SARE.

- Apitronics – solar powered a wireless data logging network that can support thousands of sensors per node with communication up to 8 miles between nodes. The first production run was Kickstarter funded.

- Cow/farm tracker - A Farm Hack project to develop a $20 per tag cow tracker that is precise within an inch and can indicate cow head position to determine grazing behavior, which could be used for other animals or objects. The prototypes are being developed with USDA/SARE funding.

- UAV and Kite imaging systems - Both Public Lab and Farm Hack projects presented multiple $300-$2000 solutions, some of which were funded by Kickstarter campaigns

- Infogram and spectral workbench – Public Lab hardware and software for multispectral cameras and spectrometer kits for smartphones. Funded by several Kickstarters.

Each of the projects presented at the 2014 iFARM event was built upon the accumulation of other open source technical accomplishments. Case studies presented in later chapters review the open source design methods used in the development of these tools.

It is not surprising to see so many variations and simultaneous and similar combinations of hardware and software. In his book, *What Technology Wants*, author Kevin Kelly introduces the theory of parallel innovation, which states that when conditions are ripe, simultaneous and similar solutions emerge, just as complex eyes in mollusks, birds and mammals have evolved many times through convergent evolution. Examples of such parallel solutions are the simultaneous inventions in multiple locations without coordination of the light bulb, the sickle bar mower, and the airplane (Kelly 2010). A similar phenomenon is now being expressed in the proliferation of networked environmental sensors. The rapid trajectory and evolution of observation technologies is illustrated in Figure 17 by the change over three years in technology used at a series of iFarm events.

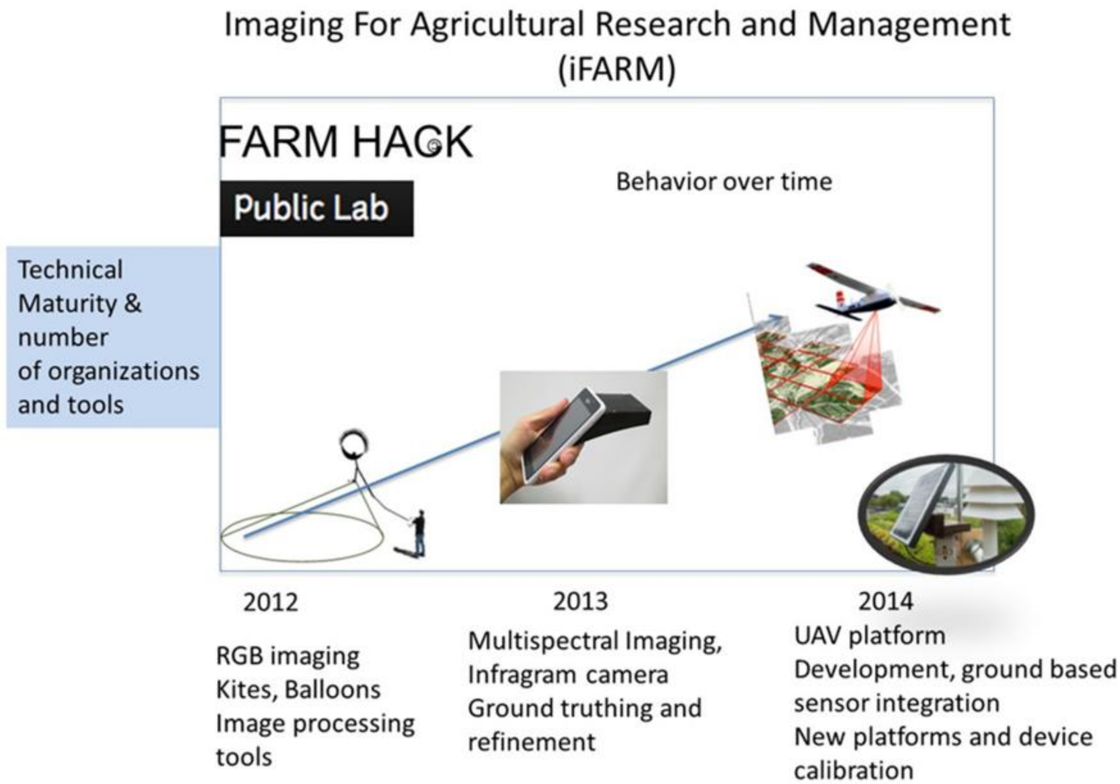

Figure 17 – Three years of iFarm learning community's technological evolution. The trajectory of iFarm technology presented and demonstrated by the Public Lab community illustrates the rapid change of low cost observation tools available. The change in technology also illustrates the evolution of community technical skills and the cumulative nature of technological capability within a learning community. Each year, new tools were added, and previous tools were tested and refined. The refinement and change from year to year illustrates a responsiveness to rapidly changing technology and communication across open source communities.

In 2013, Jeffery Warren, co-founder and research director for Public Lab, proposed that the *community driven* and *intentional* process of data gathering and analysis be called "Small Data." The term is used to differentiate it from "Big Data", the anonymous collection and analysis of data from sources that may or may not be intentionally participating (Warren 2013). Small data approaches are covered in more detail in chapters 10-13 ("Public Lab: iFarm Tech Talks" 2014), and in the forthcoming Chapter 6 of the Textbook *Digital Governance* (D'IGNAZIO, Warren, and Blair 2014).

Moore's Law and Implications for Sensor Networks

Technical achievements in the last few decades have made ubiquitous environmental monitoring possible. Key technical achievements in transistors, storage, imaging chips and other advances are now percolating through markets as the capabilities increase and costs drop, enabling embedded networked technology in tools that "talk" with other tools which leads to the expansion of the Internet beyond human participants and into the realm of the "Internet of Things." New applications for lower cost computational power and data collection span the micro to the macro, from genetic sequencing, to documenting complex plant to plant and plant to root to soil interactions (Jones 2008), to nutrient cycling across landscapes (Li et al. 2012) and global bio-geochemical pattern recognition and modeling (Lal 2004).

These discoveries and accomplishments have had a compounding effect, just as precision machining enabled the building of better and more precision machines. Moore's Law states that over the history of computing hardware, the number of transistors in a dense integrated circuit doubles approximately every two years. The law is named after Gordon E. Moore, co-founder of Intel Corporation, who described the trend in his 1965 paper (Moore and Fellow 1998). This trend has continued for more than half a century. His prediction has proven to be accurate, in part because the law is now used in the semiconductor industry to guide long-term planning and to set targets for research and development. The capabilities of many digital electronic devices are strongly linked to Moore's Law: quality-adjusted microprocessor prices, memory capacity, sensors and even the number and size of pixels in digital cameras(Lockwood and Pavesi 2004). Moore's law describes a driving force of technological and social change, productivity and economic growth in the late 20th and early 21st centuries.

The following figures illustrate the dramatic decrease in pricing and increase in capacity over the last few decades. According to internetworldstats.com, 39% of the global population now has Internet access which represents a 677% growth in just the last 14 years. The trajectory for the next 14 years is still emerging. However, the pathway that started with the linkages between computers and people has already extended to the linkages of things to the internet and hyperlinking data and meta-data generated by ubiquitous sensors across the globe. Professor William Webb, CEO of computer component manufacturer Weightless SIG, has a vision of 50 billion connected devices with chipset costs below $2, battery life of 10 years or more and a range of 5km or more to ensure ubiquitous coverage from a low cost network (Weightless.org 2014). Two billion smart phones are projected to be in use in 2015, illustrating that the process is already underway, with mobile technology becoming the fastest growing segment of internet connected electronic devices (Emarketer.com 2014). The printing press provided access to cumulative knowledge. This next phase begins a process that moves beyond sharing information and knowledge, as feedbacks and modeling begin to form networked intelligence. How and for what purpose that intelligence is used has yet to be determined.

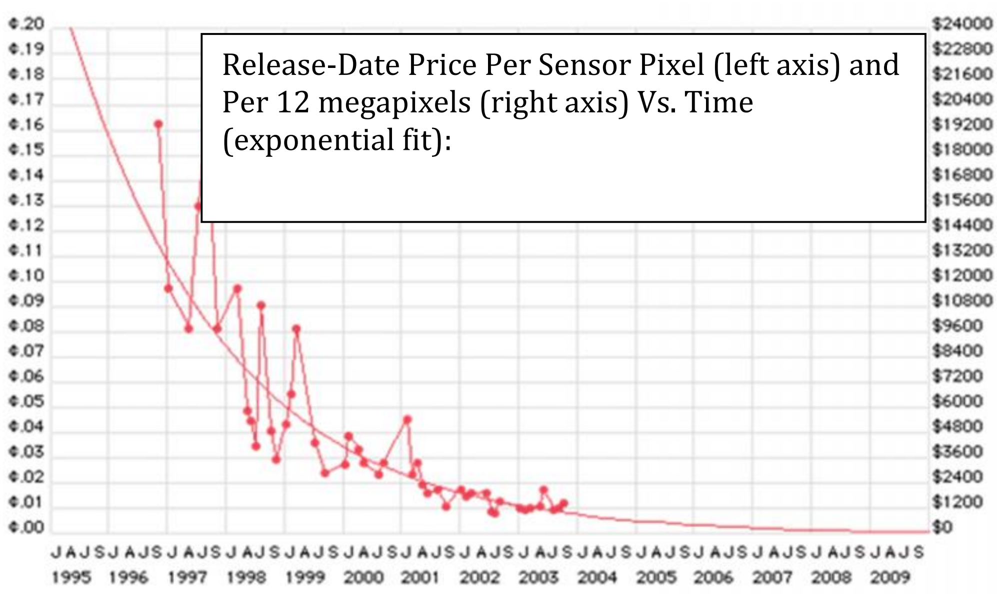

Figure 18 – Cost and capacity of imaging chips 1995-2009 (dpreview.com, 2014).

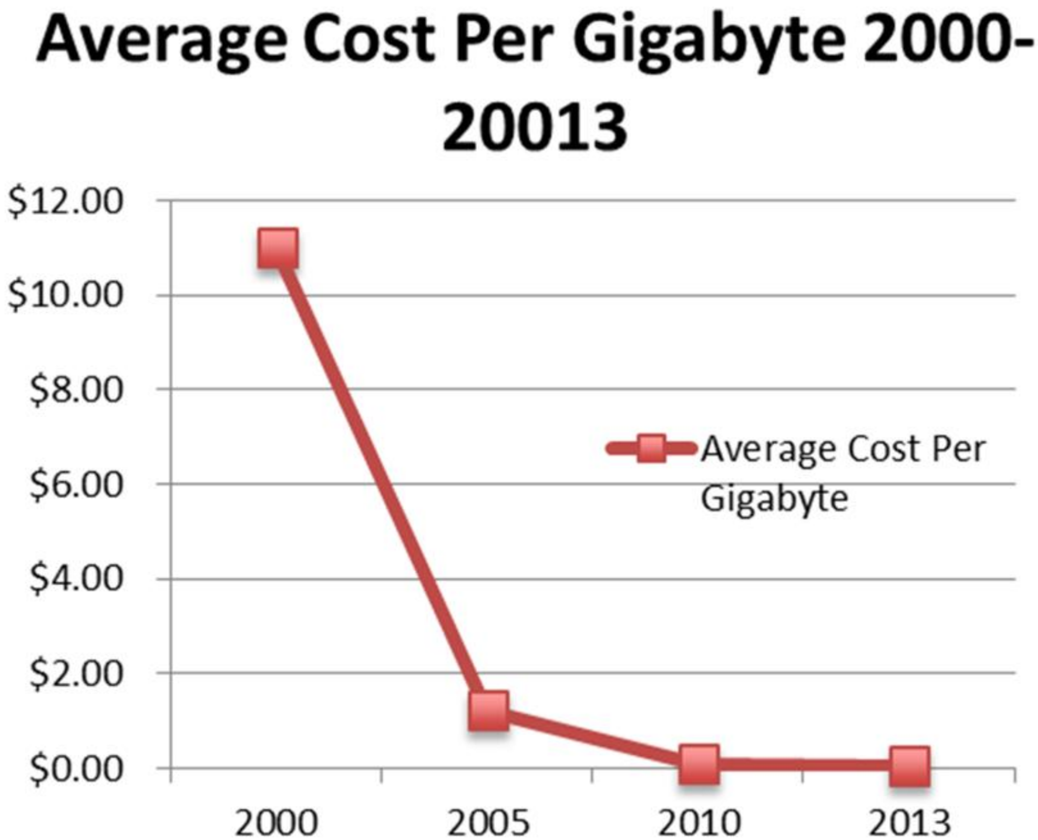

Figure 19- Continued drop in Cost per Gigabyte of storage 2000-20013 (statisticbrain.com, 2014).

Figure 20 –Networked Remote Sensing expressed as a smart phone. Low cost transistors, memory, imaging chips and sensors converge to form a social networked remote sensing technology expressed as a smart phone (Lane et al. 2010)**.**

These lowered costs are already found in electronic toys, digital picture frames, home automation, automobiles and, most importantly, as illustrated in figure 25, in smart phones that form the basis for a complex and powerful remote sensing tool.

Some environmental applications use the phone unmodified in consumer form (networked imaging) as a “base” for hardware plugins such as the FLIR Systems $300 thermal imaging camera, EcoSyth or the Public Lab developed spectrometer, or the sub components to build new custom devices such as UAV autopilots, which also add additional sensors such as barometers, thermal sensors and internal compasses (APM). However, this same drop in costs has not yet been applied to closed source, commercially available environmental monitoring equipment. At the time of writing, the cost of commercial UAVs and data logging companies maintain a 10x markup from the equivalent costs of hardware components and open source software. This type of markup moves the price point of a powerful research tool from $1,000-5000 to $10-60,000. These price points were gathered based on a survey of published prices of the leading UAV vendors marketing to agricultural uses including, but not limited to, 3D Robotics(http://3drobotics.com/), Precision Hawk (http://precisionhawk.com/), and Trimble (http://www.trimble.com/unmanned/).

Figure 24 illustrates the price breakdown in the form of a sample bill of materials for a fixed wing UAV with off the shelf components acquired as part of this study.

Function	Description	Approximate Price
Imaging	10-14 megapixel cameras. IR filters are $10	$50-$350
FPV	Live video streaming 5.8ghz transceiver system	$150-600
Navigation	Autopilot	$200
	GPS & compass	$80

	Ground station software	$0
	Navigation telemetry radios 915m hz	$30-100
	Laptop or tablet to run ground station software	$500-1000
Power system	Lipo Batteries	$15-100
	Speed controllers	$20-40
	Servos and connectors	$20-50
	Motors and props	$13-40
Airframe	EPO and carbon fiber airframe kit	$50-250
Manual Radio control	2.4ghz systems with receiver	$50-250
	Total approximate cost range including ground station computer	$1200- 3000

Figure 21 - UAV Bill of Materials. This table indicates a mix of proprietary and open source hardware and software. The systems and their assembly are well documented in publicly available forums and open source communities. Closed source solutions are not documented because the bill of materials and software components are not publicly available. There are many suppliers, however the hobbyking.com and 3DRobotics companies are the primary suppliers for this bill of materials.

The price disparity between open source and proprietary systems provides an illustration for the power of open source publishing as a cultural check to the extractive bent of market tendencies (Gillespie 2006). The same disparity is seen now in other scientific instrumentation, data loggers, and other hardware (Pearce 2012). *The New Yorker* magazine published an article on Open Source Ecology (OSE), a nonprofit focused on generating open source documentation of the fifty tools it deems critical to build civilization. OSE claims the advantage in avoiding extractive pricing by distributing the research and development risk, and reducing speculative production and support infrastructure (Eakin 2013). By its nature, an open source community is its own support structure and learning community.

Open Source Development Trends

A summary of a survey by Black Duck Software, a leading for-profit open source software company, reported that open source projects grew from just tens of thousands in 2006 to over a million projects in 2012 and the number of projects is projected to double by 2014 ("The Eighth Annual Future of Open Source Survey | Black Duck," 2014). The same survey also found that the number one reason for this growth was the better quality of software, large libraries, and freedom from vendor lock that is an inherent tendency of proprietary systems. The same report concluded that open source projects lead with innovation, collaborative partnerships, development methods, and attracting developer talent. All of those factors are important to the free flow of knowledge and are relevant to accelerating the research and development cycles for environmental monitoring projects and increasing public access to environmental knowledge.

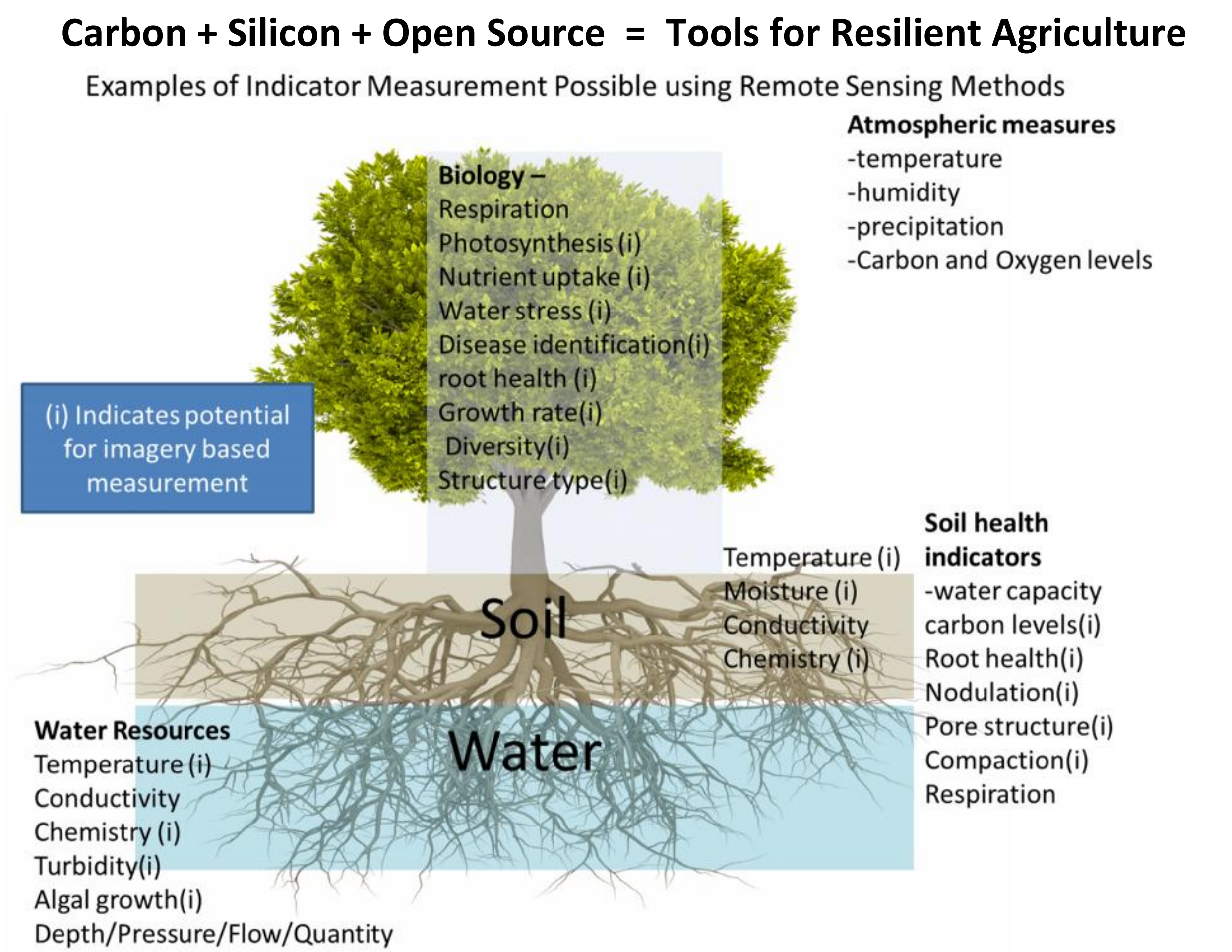

Figure 22 – Governance of Nature through data. Potential systems indicators that could be measured by imaging and network sensors to provide feedback for adaptive management. Mirabeau's tree provides a backdrop and "field of view" for the measurement and integration of whole systems health. The figure also illustrates the interdisciplinary merging of observation and analytic technology to communicate biological systems activity.

The factors already covered that have led to a dramatic cost reduction, accuracy increase, and accessibility of observations that have substantial implications for resilient soil and soil health. Figure 22 illustrates example indicators which can be used to record and communicate indicators of environmental systems health. The list and distribution illustrates that most of the biological indicators are measurable through imaging systems. Biological life forms follow relatively consistent structures that are comparatively more visible than atmospheric and soil chemistry. Other indicators rely on more specialized sensors or laboratory processes. Resilient/regenerative agriculture management requires rapid feedback to enable effective adaptive management, and the speed of acquisition of image-based analysis is also a logical fit for biological monitoring. As previously discussed, *changes in technology have rapidly altered what can be measured, who does research, what questions are asked, how it is funded, where it is done, how we communicate the results, and how those results feed back to mental models of our own world.*

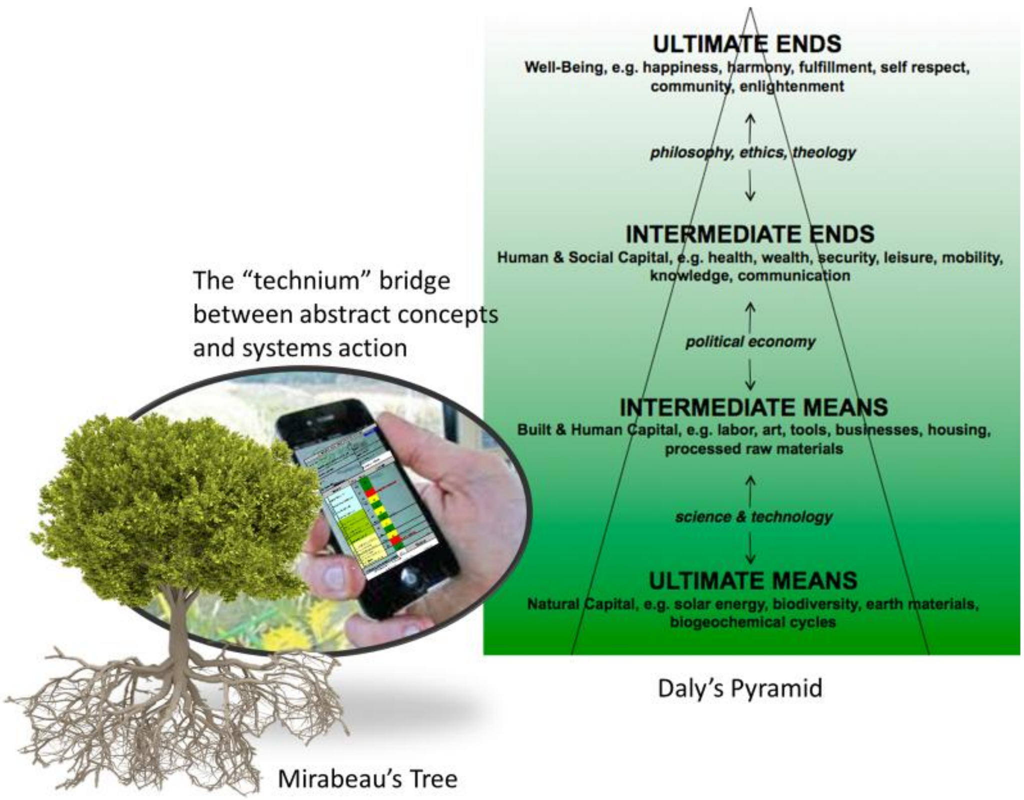

Figure 23 – The "technium" is a term coined by Kevin Kelly to describe the evolutionary forces at play with technological development (Kelly 2010)**. The interface of observation and analysis technology enables the joining of Mirabeau's tree metaphor to Herman Daly's Pyramid metaphor. The pyramid metaphor expresses the movement of ultimate means (natural capital) to the ultimate ends (human well-being). In Daly's metaphor technology and built capital are intermediate means to ultimate ends. Kelly's observation that tools are a reflection of human understanding of their environmental systems creates new insights to Daly's model and links to the operating model of Mirabeau's Tree.**

Figure 23 identifies a category of technology in the technium mirror that is observational, and informs systems understanding critical to natural systems management. The "activity layer" is within the intermediate means category of Daly's pyramid structure. The intermediate means is where scientific technology and political economy interact. As this network of tools/technology is applied, it has a particular place within the social tree metaphor. Daly's pyramid is useful in terms of human made structures based on natural resources (ultimate means) and how they relate to our ultimate ends of human well-being (Daly 2007). The pyramid is a method of interpreting the human outcomes of the Mirabeau agro-sociological tree, and the technium is the means of doing so. The Kelly technium layer provides a mirror back to the social capital structure and enables feedback to systems' environmental, economic and social health, and structural balance.

Chapter 5: Framework for Adaptive Management

Indicators as building blocks for systems health analysis

> It is difficult and often even impossible to characterize the functioning of a complex system, such as an eco-agrosystem, by means of direct measurements. The size of the system, the complexity of the interactions involved, or the difficulty and cost of the measurements needed are often crippling. However, environmental indicators can be measured and reported at different scales. For example, a town may track air quality along with water quality and count the number of rare species of birds to estimate the health of the environment in their area. Indicators are developed for specific ecosystems, such as the Great-Lakes in North America. National governments use environmental indicators to show status and trends with respect to environmental issues of importance to their citizens (Walker et al. 2004).

As previously discussed, adaptive management is dependent on rapid feedback to function. Adaptive management is a process of constant research, with the value of that research focused on management. The nature of adaptive research data means that it is far more valuable in aggregate than in isolation. Data that was once extraordinarily expensive and challenging to acquire and work with becomes accessible, inexpensive, and easy to share. The dynamic also provides an opportunity to codify the complexity of adaptive management into a more universal and adaptive cross-disciplinary framework.

The key elements that have already been identified are derived from the Soil Health Reporting process (which is presented in more detail in the systems application and social analysis section) and are as follows:

1. **Indicators are user defined -** characteristic that could have unlimited variations and cross disciplinary applications.
2. **Values –** actual measured (or calculated) values
3. **Ratings** - values as they rank with others within the database
4. **Health –** combination of ratings of groups of indicators
5. **Systems Health –** larger aggregations of health groupings

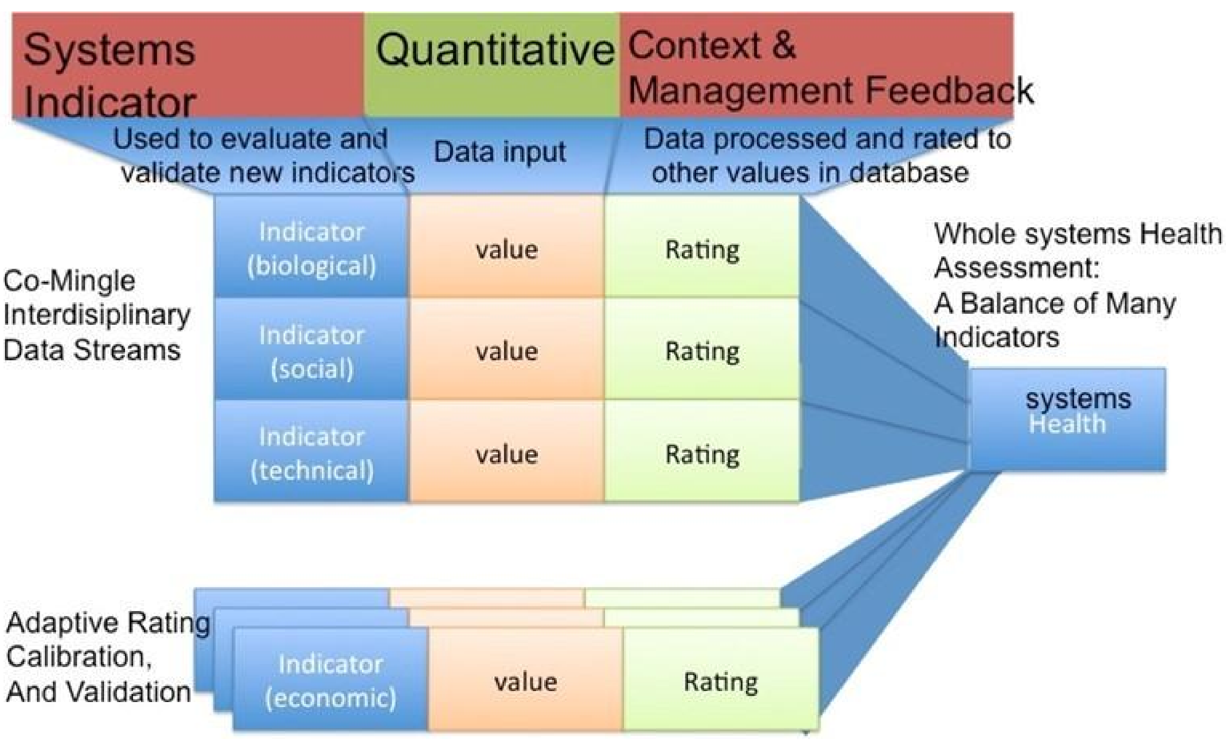

Figure 24 – The generalized adaptive framework expands to enable the creation of cross disciplinary indicators. Low cost indicators can be developed without field measurements. For example, measuring pounds of gain (beef) to inches of rain uses financial recordkeeping and weather data to provide an indicator of soil health. The

generalized structure enables new combinations of indicators to be developed and compared to other indicators. These diverse measures can be evaluated and compared in social software in a "farmer dashboard" structure such as the Cornell Soil Health report.

Indicator - The indicator is the basic building block for adaptive management. It is the focus of the development of this model and enables the validation of new culturally assimilated indicators into the workflow. The proposed framework also enables expressed social values through Mirabeau's tree as well as through the adaptive management approach outlined here. Networked communication technology also makes it possible to record this process and these relationships not just in writing, but in code. Some potential examples of indicators that could be created include:

• Soil compaction • Net yield to nitrogen input • Total days without plant growth • Capital use efficiency • Land use efficiency • General soil health • Soil organic matter • Soil water holding capacity	• Net profit to soil health ratio • Farm labor intensity/acre • Net primary production • Net energy to soil health ratio • Monitoring frequency • Net biomass per acre/inputs • Plant diversity • Yield/pounds gain per inch of rain

Value. A measured value becomes an indicator when placed into context. The technical discussion of this dissertation spends some time examining examples of changes in technology that have altered the cost of measuring and storing values, but what makes values useful is placing them in context. The value on its own might provide some insight, but it becomes more valuable when put in context and as a measurement of an indicator of a larger system.

Rating A rating takes the measured value and puts it into a systems context by applying logic and comparing the value to other measured values already recorded. The process of applying the rating creates the human interpretation of the value within high and low baselines. It is where values are created to guide management decisions, and is the result of the convergence of science, technology and community. The quality of the rating also depends on trust and community participation required to build a quantitative context.

The Physiocratic framework, as illustrated by Mirabeau's Tree, represents a social system that places indicators within social, economic, biological and technical contexts and expresses the values in terms of the culturally accessible metaphor of tree health. The combination of indicators and associated ratings are assembled to achieve a meaningful representation of the larger system; from soil health, holistic farm management, to water quality, or watershed erosion potential.

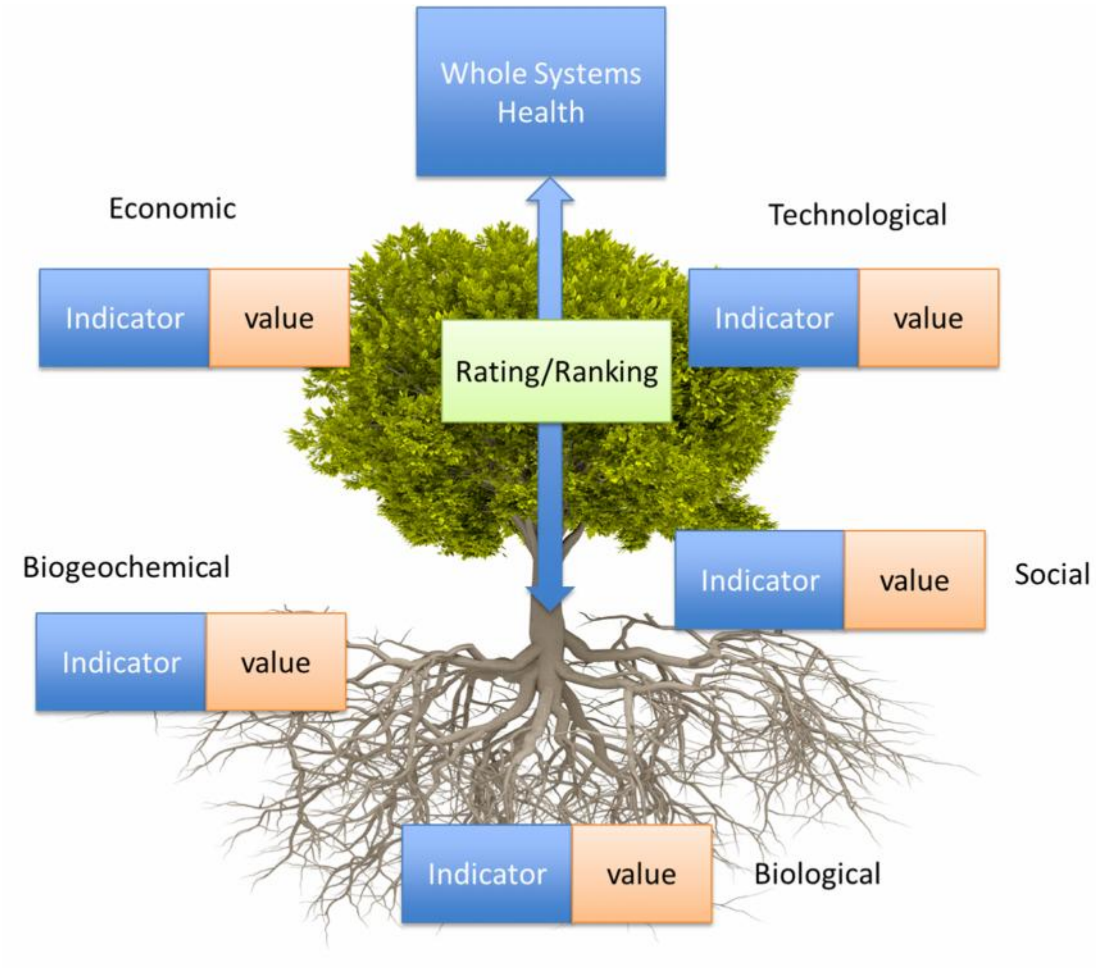

Figure 25- The application of interdisciplinary indicators to create dynamic health feedback loops. Interdisciplinary indicators can be combined and visualized as they relate to their functional relationship within Mirabeau's Tree metaphor of whole systems health. Ratios can be created between social, economic and biological interactions that otherwise might not be viewed in context. The values associated with each of the indicators can be evaluated and recombined with values from other parts of the system to create new indicators as the Figure 24 workflow illustrates.

The compilation of multiple indicators and their relative ratings provides a quantitative rating first of sub systems health, such as soil health, or whole systems health as outlined within the Physiocratic framework. Without the indicators and metaphors, the system becomes too complex to comprehend or manage with some level of informed decision making. The adaptive management applied to the Physiocratic framework recognizes that the first indicators will not be the most accurate, but they can be used to prod the system, and to develop and validate new and more accurate indicators.

These relational elements also form the basis for an adaptive research process that can be used as an applied methodology and codified into an adaptive management software tool. One of the primary challenges of cross disciplinary research is the siloing of data and methods for integrating disparate types of data. This universal relational structure provides a conceptual interface to that problem, and also a method for evaluating the quality of the indicators chosen. For example, in the process of using this framework for soil health the general indicators provide guidance to focus efforts, after which particular values come into play. The actual values may or may not be actionable by themselves, but ratings provide a context and logic to what that value means in a social context and in relationship to other values already recorded in the database. Individual ratings can then be placed within a broader context to further prioritize adaptive action. Some indicators may change slowly and others more quickly, but by being socially connected and in aggregate, they can be evaluated in context.

The use of indicators embraces an approach of observation of emerging systems behavior with an assumption that the system cannot be wholly known, but that patterns in behavior can be gleaned from inductive observation. The focus on inductive observation also enables the identification of common questions that bridge disciplines. The indicator approach does not ignore deductive approaches but instead inverts the process to build upon specialized knowledge after focusing on common unknowns and questions.

Indicators may emerge from farmer- or research-generated data from sensors, recorded observations, spreadsheets, accounting software, and/or climate and nutrient models already in use for farm management decision-making; however, these indicators are frequently presented without context and often in low frequency. The calculations and data also tend to be inaccessible, locked up in spreadsheets or obtuse academic software that are difficult to maintain even for the modelers. The alternative is accessible, affordable adaptive management software that shifts a portion of the data collection and ownership to the farmer, and which invites further participation and collaborative exploration with a supporting role of data aggregation, processing and value added interpretation from scientists and professional service providers. To become more adaptive and engaged in the broader feedback loop of agricultural research, farmers can adopt tools that generate large quantities of high resolution data through environmental monitoring technology and online farm management software that have value beyond their immediate management goals.

Web APIs (application programming interface) methods create linkages across platforms through agreements and contracts. Researcher-built models such as Web Apps can now use Web APIs to enable farmers to access indicators calculated countless times in a season, with little or no delay. Based on an adaptive management software framework, an open source platform could enable researchers to easily access live data sources that could be validated against other indicators within the system and made available through Web APIs.

Figure 26 – Observation technology applied to a landscape. This diagram illustrates the application of currently available open source observation tools in a landscape context. The collection of these remote sensing tools is combined within this context to provide high resolution feedback required for collaborative adaptive management. These include, from bottom left moving clockwise, smartphone based imagery, Apitronics and Fido networked ground sensors, UAV based aerial imagery, FarmOS software, ubiquity wireless wifi bridges, and riffle water sensors and data loggers.

The potential is a greater quantity of biological, economic, and social data, documented at higher frequency, controlled by agreements with farmers available over Web APIs to both technical advisers and researchers. Decision-making support using rapid and accurate feedback is a pre-condition for effective adaptive management.

Examples of Web APIs for agriculture in development (also covered in later case studies) are:

1. **Hive** - Publishes a Web API for environmental data collected from an on farm sensor network.
2. **Farmier/FarmOS** - Publishes a Web API for farm management data that is entered by a farmer for management, order processing, and record keeping.
3. **Cornell Soil Health Lab –** Web API (in development) for soil health data to be collected on-farm and lab-processed.

With these data sources available in real time and combinable in another Web App, the indicators can be customized, recalibrated, and shared in many custom combinations. Data portability is made possible through standardizing the data format such as column headers in CSV files. The Web API creates a bridge to carry that container across to other APIs.

The bridging enabled by Web APIs means that factors such as soil compaction ratings and pH can not only be tracked but also combined with financial and management record keeping data, which can be imported using the same framework as a value and indicator, and related to other indicator descriptions. The Soil Health Report uses a weighted model to generate ratings and total soil health scores, similar to weighted financial modeling. The creation of a universal adaptive model enables the combining and re-combination of financial, biological and technical models that can accommodate any type of biological, social, technical or financial data flow, and create meaning from relationships of individual values relative to data within the database. This type of holistic health rating system enables the development of far more sophisticated ratios and indicators over time. Until recently, many systems interactions have been too complex to quantify, such as yield-to-input indicators, and yield-to-weather indicators, to measure resilience and environmental efficiency. These interactions can now be analyzed. These measures also enable managers to assess more sophisticated relationships, such as herd health, soil health and net margin. It also provides a framework for developing new adaptive measurements. Many indicators have not previously been practical because of the high cost of measurement and recordkeeping.

Faster indicator feedback is a required condition for improved adaptive management (Walker and Salt 2006), and creating software systems that codify the feedback process and refine the value of indicators in the process is a step toward making adaptive management a reality. A more detailed discussion of this framework continues in the technical section; this framework provides the organizing principles of the social technology and data flows described within the applied social analysis section, as well. The shift to using machine-based observations and processing to create new observations from data collected in an unbiased approach creates new considerations for the balance between inductive and deductive research that makes adaptive management possible. By its nature of making broad observations first, an inductive approach focuses more on the search for unknown patterns. The unknown will always be greater than the known, and this condition of shared wonder therefor creates common ground across fields of study and accommodates the interdisciplinary nature of systems exploration and management.

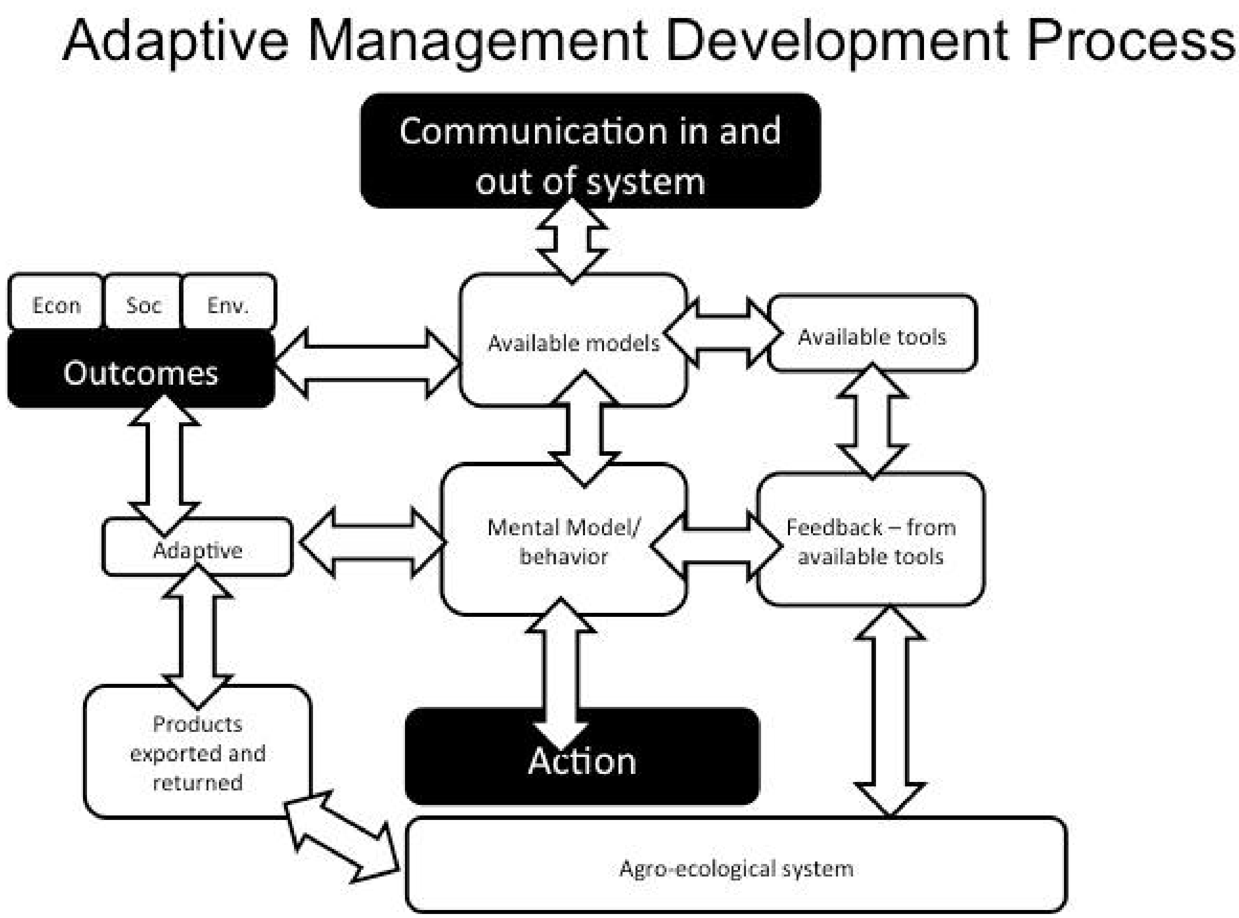

Figure 27- Adaptive Management flow from knowledge to action. This flow diagram illustrates the implementation of adaptive management and a constant flow of knowledge feedback loops. Adaptive management requires feedback of appropriate knowledge at the appropriate time to take action. Reactions and feedback times from those actions are then taken into account for future actions, but are limited by feedback cycle times. The complexity of the data and interpreting the feedback from indicators illustrate the role of computer aided support to gather and accelerate the interpretation of knowledge to enable action.

Figure 27 applies the technium-aided quantitative adaptive feedback model to land management. In this diagram, the primary flow is knowledge to action. Tools, action and environmental feedbacks are all knowledge based. Incomplete information for social, or technical reasons would be symbolized by blockages, or restrictions to the feedback process. The result of knowledge restrictions are expressed in reduced systems understanding and inadequate feedback and ultimately in missed opportunities to take the most effective action. If, however, this model is applied effectively, it can create a positive, reinforcing feedback loop as illustrated in figure 28, again using Mirabeau's Tree metaphor.

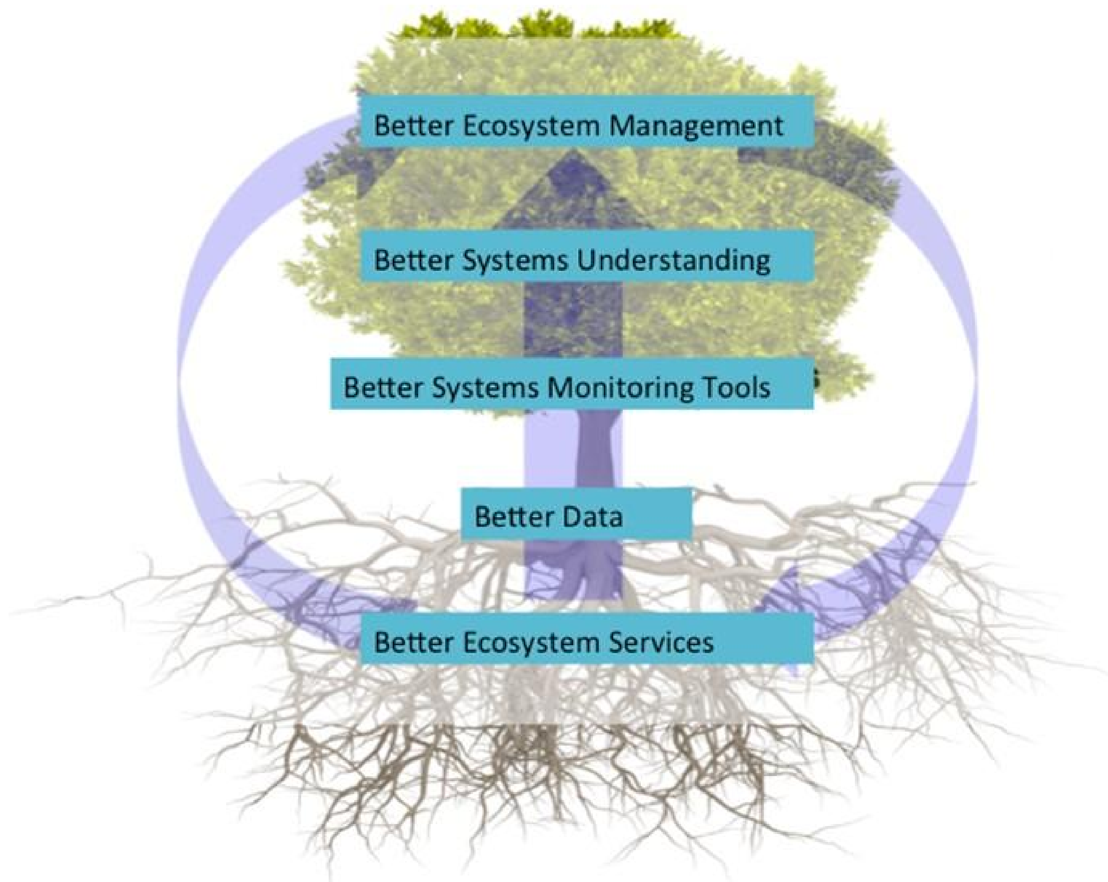

Figure 28 – Cumulative systems knowledge, improved tools and Adaptive Management. The adaptive management process overlaid on Mirabeau's Tree illustrates the process of Figure 30 put into societal context. Feedback from biological and agricultural systems flows through to reflect itself in improved observational, analytic and action tools. The refinement of tools and communication tools leads to improved systems understanding which can feed back towards improved management decisions. The feedback process is aided and parallels the development of the "technium".

The complexity-to-accuracy ratio of ecosystem monitoring tools is not necessarily a linear function. An indicator that is more complex to measure is not necessarily more accurate; however, simple and low cost indicators may be challenging to identify and subsequently validate without methods that may at first be complex. Neural network and machine learning methods make it possible, for example, to identify visual spectral signatures of nutrient deficiency in leaf tissue that are easily identified with the unaided eye, but to validate that observation may require complex and expensive laboratory methods to build spectral libraries and databases to increase the accuracy of field observations. As validation through greater levels of participation is made possible through social technology and reduced barriers to knowledge exchange, simple observations may be made more powerful through context gained by access to a wider network of observations. A non-technical example of this is general knowledge of species identification. Most New England residents are likely to be able to identify poison ivy, but probably not fungal growths on barberry leaves; this is not a matter of complexity but of cultural assimilation of environmental indicators. However, simple ID protocols could create a simple automated leaf color and ID tool like leafsnap.com which is being developed by the Smithsonian, University of Maryland, and Columbia University. Figure 29 illustrates this process of technology aiding in cultural assimilation of knowledge. It describes simple observations made powerful through high tech validation and networked data management.

The power of systems integration is in the pace of iterations, validation of new indicators, and the ease and speed of communication and adaptation of management by participants (Lee 1999). An example of this is illustrated using a comprehensive Scottish soil data base coupled with low cost imagery in the visual spectrum taken with low cost color calibration cards included in-frame (M. J. Aitkenhead et al. 2013). The images were then fed through a neural network to process the images remotely, and return the analytic results. The project relied on The National Soils Inventory for Scotland (NSIS), which contains soil and site conditions of 3094 locations throughout Scotland sampled for physical and chemical properties using a 5 km grid across the entire country (M. J. Aitkenhead et al. 2013). The project demonstrated that a neural network approach to the prediction of soil parameter values could consistently produce $\mathbf{r}^2$ values of >0.5 for parameters relating to texture and broad physicochemical properties such as organic matter. Such an approach is an illustration of a rapid and cost-effective method for providing soil analysis that can be applied by soil professionals and land users with little expertise in the field (M. J. Aitkenhead et al. 2012).

Aitkenhead (2013) builds on the initial promise of this approach and experimenting with a system that will work with mobile phone cameras to link with server-side data processing, and enable the progression from data acquisition to useful landowner feedback. The same infrastructure used for this approach is already in use for web-based mobile phone applications used in agriculture and public health. Fields such as ecology and public health are more restricted to case-based inductive methods of observation and analysis because of ethical concerns, and have established methods for data gathering and processing. Changes in machine learning, artificial intelligence, and big data quantitative methods make these methods more powerful, and expand the potential for re-application in other fields.

Aitkenhead (2013) illustrates the role of a manually collected ground-truthed dataset such as the National Soils Inventory for Scotland (NSIS) for calibrating and automating participatory low cost systems based on image analysis. This process is actually discovering, exploring, and creating hyperlinks between images and metadata cumulatively provided by users, based on the content inside the images. The amount of semantic interconnection and the amount of richness that comes out of the system expands with use and becomes larger through the classic network effect. The extension of this process, taken to extremes, is a model of the entire Earth and the way the Earth works.

Complexity to Internalization Curve

Complexity has characteristics that are emergent, unexpected and unpredictable. Simplicity, in contrast, is the creation of inexpensive, predictable, and reproducible results that can be built upon and re-combined. For example, the internet is built on the most simple building block possible in patterns of binary code, running on a series of switches in the form of transistors that can repeat very simple actions billions of times without failure. The simplicity, and dependability of those building blocks is represented in the scale of complex, but largely invisible forms that make the simplicity of the an Internet search bar possible. The simplicity of transistors and binary code is also what makes possible the complex network that enables people who do not know how the system works to benefit from the cumulative knowledge upon which the Internet is built.

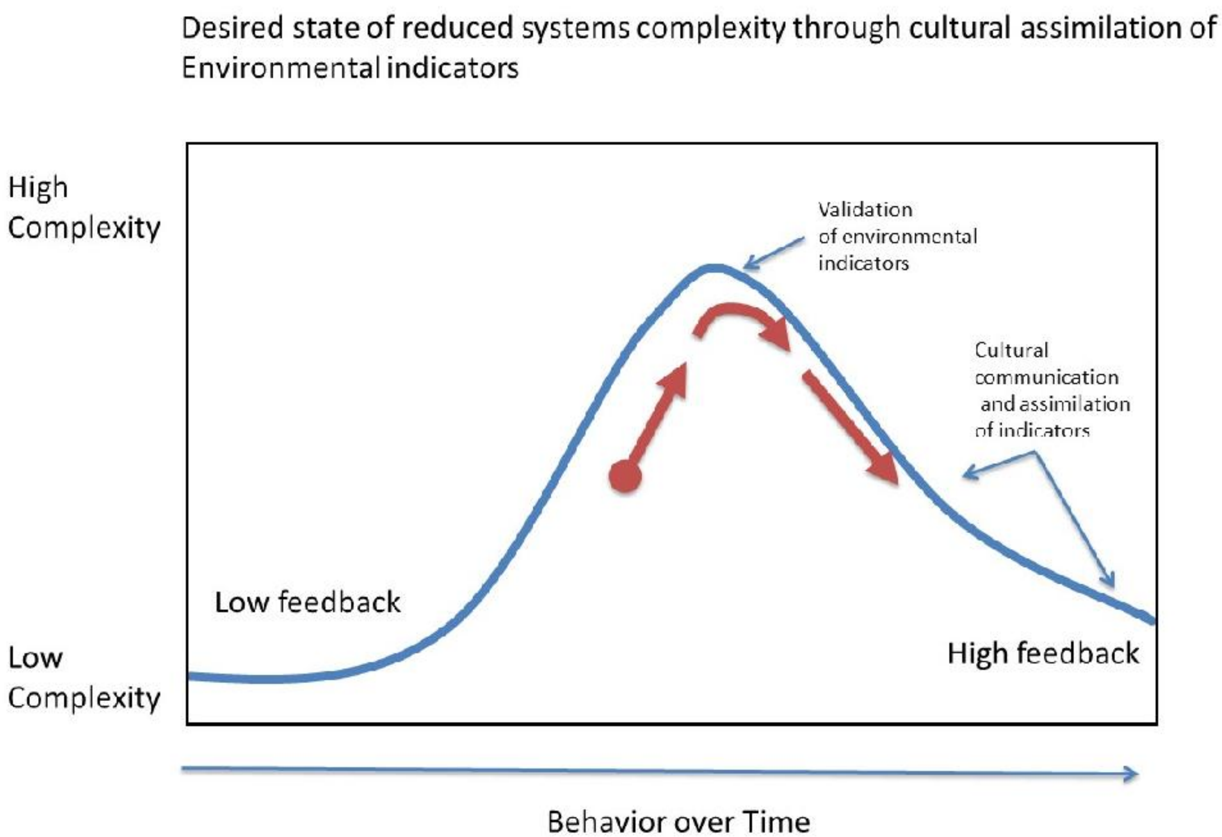

Figure 29 – Complexity curve of indicator validation. This graph illustrates the logical process of increasing complexity as indicators are validated, but then the decreasing complexity of indicator measurement once lower cost indicators are both validated and become culturally internalized. The iterative process of adaptive management and generalized approach to indicator evaluation and validation (Figure 10) is aimed at narrowing down to fewer, more simple, and more accurate indicators over time.

Photosynq, an open source community based out of Michigan State University, provides another example of movement along this curve. Like the soil imaging project, it is building a model based on observable biological characteristics, and working towards an online spectral library to evaluate plant health.

Photosynq's open source platform intends to create a global database of plant health around the world by linking individual users together with low cost but powerful scientific instruments that connect to smart phones. They are, in essence, attempting to move along the complexity curve illustrated in figure 36.   Photosynq is also aiming to create the tools, collaborative space, and social community to support their effort.   The basic work flow from the Photosynq web site is as follows:

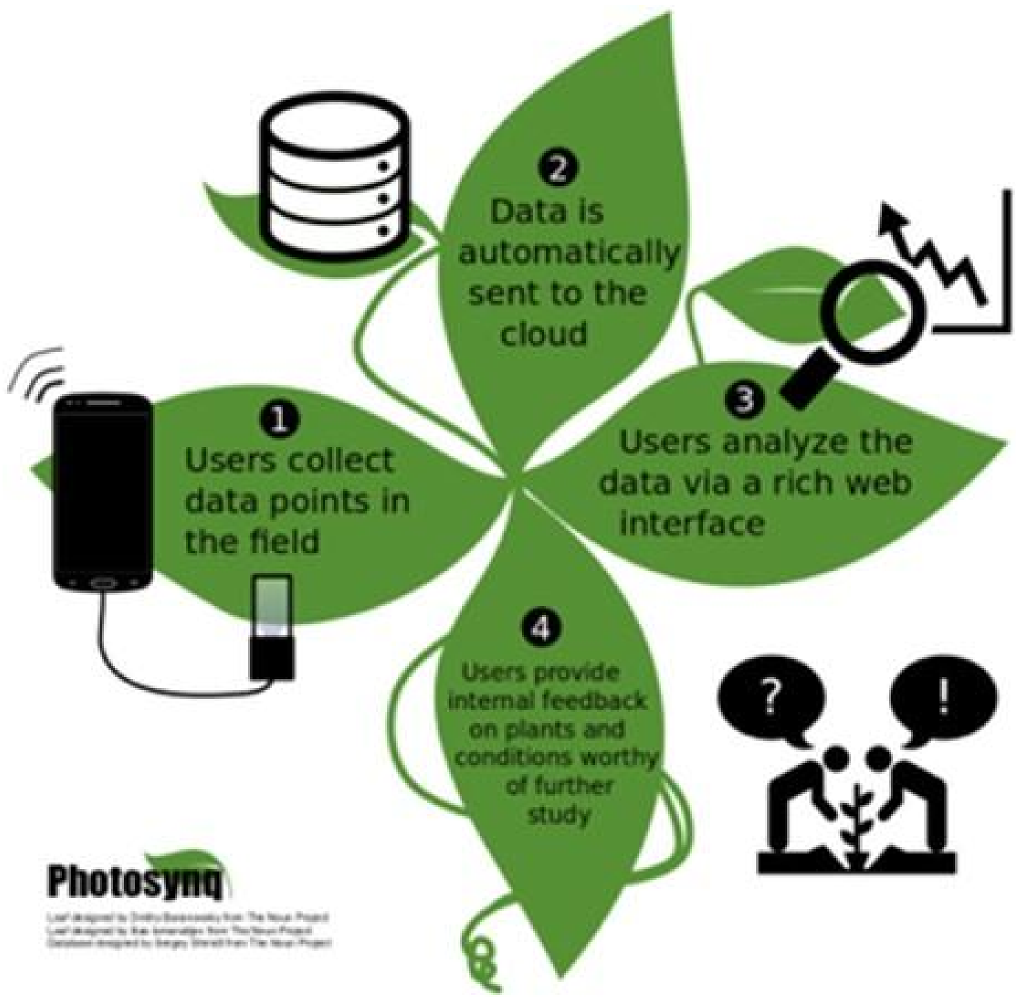

Figure 30 – Collaborative networked data collection and analysis illustrated by the Photosynq process ("PhotosynQ - An Open Reseach Project" 2014).   This process relies on high resolution, low cost networked field hardware that feeds into databases for aggregation and analysis which is conducted through online social and collaborative software.

1. Raw data collected by the phone is sent wirelessly to a database where it is compiled. The remote sending data includes florescence, light level, absorbance, leaf image, date time, and GPS location (other raw data could also be collected by other sensors and platforms identified).
2. All data submitted to the database is available to everyone else in the community for analysis. Some of the measurement protocols include LED brightness, Pulse timing, Amplifier gain and Sample Rate.
3. The data is then fed back into a user-friendly web-based interface to enable collaborative analysis and community conversation support and feedback.
4. The common platform links applied scientists with researchers, educators, and citizens to create a participatory network.
5. The interface and network architecture can support inquiries of multiple temporal and special scales, based on the community need.
6. The result is a combined research and experiential education platform that serves both applied and foundational work at the same time, and incorporates outreach into the process. ("PhotosynQ - An Open Reseach Project" 2014)

The process grows in complexity as people use it, and its benefits to the users increase *as they use it.* Participants' photos are tagged with meta-data that somebody else has entered, creating immensely rich virtual models of plant life collected not just from overhead flights and satellite images, but from collective memory and broad-based participation.

Implications for Experimental Design

Changes in technology, and the reduced cost of complexity due to the lowering cost of data storage, processing, and observation, have implications for the basic economic principles laid out by Ricardo related to comparative advantage and specialization (Ricardo 1821). If particular knowledge can be made universally accessible through collective intelligence, then the process and cost of asking questions will have a profound impact on the structure and financing of research. The economics of an inductive, participatory approach to science, which requires vast quantities of impartial data to overcome biases and limitations of perspective, is just now becoming possible; the shift in observational technology and big data methods opens up the opportunity for greater participation with experimental design as research becomes more accessible, less expensive, and more accurate.

Experimental design is often structured to facilitate data collection and to accommodate the statistical challenges of processing the results. Riley and Alexander (1997) provide examples of alternative approaches for participatory research design and include "augmented designs which involve a large number of unreplicated treatments organized into very small blocks, with as few as five experimental units (Lin and Poushinsky, 1983; Casler, 2013). Another approach is to use a center plot within each block consisting of a single cultivar that serves the purpose of error estimation and spatial adjustment on a large scale. Additional check cultivars are added at random to individual blocks to augment error estimation and to estimate the spatial effects on a finer or smaller scale (Lin and Poushinsky, 1983).

Mother-daughter designs have recently emerged as a variation of this theme in the field of participatory research (Snapp et al., 2002; van Eeuwijk et al., 2001). These designs are generally focused on a small number of practical treatments in which farmers or small landholders have a genuine interest and/or a sense of ownership. The most traditional application involves the use of a “mother” trial, conducted under traditional parameters at a research station but also accompanied by numerous “daughter” trials conducted by participating producers. Mother trials usually include all possible treatments, while daughter trials generally include a subset of the treatments of interest to the producer. Individual producers are able to choose which treatments are of the most value to their own operation. The daughter trials are linked together by the fact that they are also replicated in the mother trials and many treatments are repeated across multiple daughter trials (van Eeuwijk et al., 2001). If participation is part of the goal, then designing experiments with relatively few treatments over larger areas is also more desirable than lots of variation on a few farms with concentrations of data (Riley and Alexander 1997).

One of the most valuable parts of on-farm experimental design is that it can incorporate both management history and diversity of conditions. Incorporating these is especially important when deliberately building complex plant agro-ecosystems and testing variety performance in diverse conditions. For example, the interactions of diverse cover cropping, inter-planting, and complex weed seed banks are hard to replicate on research stations. With the advent of computer-based statistical analysis, new types of experimental designs are possible, which rely on computer calculations rather than on the farmer (Riley and Alexander 1997). Computing power is now readily available, along with the expertise to manage complex modeling software that makes statistical processing universally available on any modern laptop.

Open Source Research Hardware

Until recently, customizing software has been much easier than customizing equipment; however, the open-source paradigm is now enabling creation of open-source scientific hardware, as well (Pearce 2012).

A transformation of popular culture through ubiquitous observation, communication, computation, and storage creates conditions that can soften the boundary of professional science with a more interdisciplinary, natural philosophy approach. Public Lab is an example of an emerging open source "citizen science" organization, describing itself as "a community where you can learn how to investigate environmental concerns." Using inexpensive DIY techniques, Public Lab seeks to change how people see the world in environmental, social, and political terms.

Public Lab represents an early adopter network-based organization that has pioneered the use of consumer grade electronics and cameras for environmental observation. A representative example of the Public Lab community projects is the grass roots mapping kit. The kit is a combination of instructional materials, web sites, software, balloons and kites with easy to build instructions for generating aerial imagery at higher resolutions than the most sophisticated satellite imagery. Public Lab's early work gained notoriety through citizen documentation of the Gulf of Mexico oil spill. Because of the open source nature of the work, which can be tracked and quantified by cross postings and shared across community memberships, Public Lab's early contributions have had a ripple effect across other open source communities, including Farm Hack and DIY Drones. The interaction among these open source communities and their technical contributions to a new systems framework will be covered in Part Two and Part Three of this thesis, respectively.

Part II – Application of Collaborative Open Source Agricultural Systems

Chapter 6: Open Source and Agrarian Systems

Literature Review

Research Approach and Methodology

Important outcomes of science are principles that explain what consistently happen in nature (Miller 2005). The research design of this dissertation used a qualitative, multiple case study approach combined with a phenomenological approach. Yin (2002) defined case study as "an empirical inquiry that investigates a contemporary phenomenon within real-life context." Phenomenology refers to how an individual or group of people attach meaning, structure, and essence to their experience related to a phenomenon (Moustakas 1994). The task of the researcher is to depict the essence or basic structure of an experience in order to find meaning through interpretation of the "text" of the experience (Merriam 1998).

This study uses the case-based method applied to open source communities which have recorded interactions using electronic media and documentation to record the "text" of the experience. This online documentation provides a rich record of community location, motivation, and contribution. The case-based approach brings insight, clarity, and interpretation to the study with the intent of describing the social links and network structures involved in innovation and sustainability. The dissertation uses these case studies and phenomenological analysis to support the proposed theoretical and social framework for collaborative adaptive management.

According to Kurt Lewin, complex systems can be best explored through action within the system, because a system's reaction to changes reveals its characteristics (Lewin 1946) ("'if you want to know how things really work, just try and change them"'). In other words, relevant issues frequently come up during the process of action, and would be missed through rigid planning (Hangmann et al, 2002). The methodology used is not a work of explaining, but rather of exploring; not a prescription, but rather an approach and structure to help guide further exploration.

Lessons from Practice

Where theory is lacking, the scientific approach must be inductive and, accordingly, theory development is based on comparative analyses of different case studies. Based on Lewin's crucial observation about systems behavior, organizational and technical experiments were developed using a systems approach – to test and observe systems behavior over time by engaging the system directly and observing the results. The creation of GreenStart and Farm Hack and their expression of biological, social, economic, and technical systems behavior are a result of such action by the author in the course of this study.

Action research is a means of systematic inquiry for all participants in the quest for greater effectiveness through participation (Joseph and Andrew 2008). Action research, as a method places the researcher as an observer, and as a peer within the social network being studied, rather than an outside researcher with an unknown agenda. The peer to peer relationship, and shared values reduces the risk of lost trust. Network development is dependent upon building relationships which may be fragile before systems behavior emerges and shared values and goals can be established. By observation through indicators and documented outcomes, systems emergence can be captured through technical achievements and social behavior expressed in actions as indicators. The existence of online documentation in GreenStart and Farm Hack forums is an expression of actions reflecting social values and interaction with other biological, technical, and economic systems as expressed in the Physiocratic framework diagrams presented in Part One. For example, the web sites created within the open source community are also published under the creative commons license, which facilitates republishing and sharing of their content and data.

Adaptive management is an ongoing and constant process of research and development and continual refinement through active feedback loops. The process assumes uncertainty rather than viewing uncertainty as a failure. The Physiocratic framework is used to provide a broader interdisciplinary systems context and associated agrarian social values within which to place the case studies.

Open Source Community Approach to Agricultural Technology

There is a clear intellectual link between historic Enlightenment values and the current open source movement (Zimmer 2009). Wikipedia stands out as a contemporary corollary to the French *Encyclopédie*, a *Systematic Dictionary of the Sciences, Arts, and Crafts* of 1751. The *Encyclopédie* was the first encyclopedia to include contributions from many named contributors and is considered by historians to be the embodiment of French enlightenment values of spreading and expanding human knowledge (Cronk 2006). The *Encyclopédie* is particularly relevant to this study both because of its participatory creation and because it gave special attention to detailed documentation of the skills of mechanical arts and crafts that previously had been ignored such as agriculture, baking, and metallurgy. It symbolized the 18th century's crusade against superstition, fanaticism, and tyranny, and its belief in human progress, happiness, and freedom (Cronk 2006). At the time of this writing, the collaboratively written web-based Wikipedia is ranked by Alexa Internet as the 6th most popular website ("Alexa Top 500 Global Sites" 2014); Internet technology allows Wikipedia to broaden the *Encyclopédie*'s mission by allowing for ongoing participation through openly editable content. Google, the most trafficked web site on earth, although not explicitly open source, has a stated mission to "organize the world's information and make it universally accessible and useful." Google's mission also echoes the *Encyclopédie* and Denis Diderot's words from over 200 years ago that captures the cumulative power of open source knowledge exchange:

> "The goal of an encyclopedia is to assemble all the knowledge scattered on the surface of the earth, to demonstrate the general system to the people with whom we live, and to transmit it to the people who will come after us, so that the works of centuries past is not useless to the centuries which follow, that our descendants, by becoming more learned, may become more virtuous & happier, and that we do not die without having merited being part of the human race."


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Random article
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Recent changes
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Tools
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Related changes
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Encyclopédie

From Wikipedia, the free encyclopedia

This article is about the 18th-century French encyclopaedia. For a definition of the word "encyclopédie", see the Wiktionary entry encyclopédie.

Encyclopédie, ou dictionnaire raisonné des sciences, des arts et des métiers (English: Encyclopaedia, or a Systematic Dictionary of the Sciences, Arts, and Crafts) was a general encyclopedia published in France between 1751 and 1772, with later supplements, revised editions, and translations. It was edited by Denis Diderot and, until 1759, co-edited by Jean le Rond d'Alembert. As of 1750, the full title was *Encyclopédie, ou Dictionnaire raisonné des sciences, des arts et des métiers, par une société de gens de lettres, mis en ordre par M. Diderot de l'Académie des Sciences et Belles-Lettres de Prusse, et quant à la partie mathématique, par M. d'Alembert de l'Académie royale des Sciences de Paris, de celle de Prusse et de la Société royale de Londres.* ("Encyclopedia: or a Systematic Dictionary of the Sciences, Arts, and Crafts, by a Company of Men of Letters, arranged by M. Diderot of the Academy of Sciences and *Belles-lettres* of Prussia: as to the Mathematical Portion, arranged by M. d'Alembert of the Royal Academy of Sciences of Paris, to the Academy of Sciences in Prussia and to the Royal Society of London.") The title page was amended as D'Alembert acquired more titles.

The *Encyclopédie* was an innovative encyclopedia in several respects. Among other things, it was the first encyclopedia to include contributions from many named contributors, and it was the first general encyclopedia to lavish attention on the mechanical arts. Still, the *Encyclopédie* is famous above all for representing the thought of the Enlightenment. According to Denis Diderot in the article "Encyclopédie", the *Encyclopédie*'s aim was "to change the way people think".[1] He wanted to incorporate all of the world's knowledge into the *Encyclopédie* and hoped that the text could disseminate all this information to the public and future generations.[2]

Contents [hide]
1 Origins
2 Publication
3 Contributors
4 Contents

Encyclopédie, ou dictionnaire raisonné des sciences, des arts et des métiers

ENCYCLOPEDIE, OU DICTIONNAIRE RAISONNÉ DES SCIENCES, DES ARTS ET DES MÉTIERS, PAR UNE SOCIÉTÉ DE GENS DE LETTRES.
TOME PREMIER.
A PARIS,
M. DCC. LI.

The title page of the *Encyclopédie*

Author	Numerous contributors, edited by Denis

Figure 31 – The juxtaposition of the Wikipedia entry on the *Encyclopédie* illustrates the compounding nature of open source knowledge exchange and the continuation of an unfinished vision of the enlightenment continued. The contemporary open source and agrarian movements are able to expand the potential vision for knowledge exchange and participation due to the dramatic changes in digital information technology.

The intellectual heritage of the open source movement is not lost on its participants.

Thomas Jefferson, for example, is often quoted within and by the movement ("Wired 2.03: The Economy of Ideas" 2014):

> "That ideas should freely spread from one to another over the globe, for the moral and mutual instruction of man, and improvement of his condition, seems to have been peculiarly and benevolently designed

> by nature, when she made them, like fire, expansible over all space, without lessening their density at any point, and like the air in which we breathe, move, and have our physical being, incapable of confinement or exclusive appropriation. Inventions then cannot, in nature, be a subject of property."

Jefferson and his contemporaries did not talk about knowledge in terms of sustainability, partly because there were still vast frontiers to the west in their minds, but also because their agrarianism was rooted in the most basic nature of regeneration and sustainability and the human cultural values imbued by the concept. These ideas were far from new even then. Pre-industrial Physiocratic thinkers like Benjamin Franklin and Jefferson drew heavily from Confucian intellectuals (Higgs 2001). In the *Encyclopédie*, to which Jefferson was a contributor, the entry on agriculture describes earlier agrarian leadership in Confucian China, stating that "in order to inspire a taste for it in his subjects, the emperor puts his own hand to the plough once a year to plough a few furrows, and his most distinguished courtiers then follow him in turn" (Diderot 1751). Although disparate in philosophical perspectives, Enlightenment thinkers shared a belief that the free flow of, and access to, knowledge was crucial to human progress and understanding of the world, and that restrictions to knowledge were a drag on human progress.

The strength of these convictions has always been in reaction to human tendencies in the opposite direction. Early American and European history was a time of great state and industrial espionage, with official restrictions on the flow of knowledge, seeds, and genetics from countries or regions. Part of the challenge to the open flow of knowledge has always been extractive pressures as a component of resource development, either applied to natural resources or to intellectual property. The tension between open source approaches and protectionism of knowledge has a long history. For example, harbormasters once fiercely protected tidal chart knowledge, using their expertise as an intellectual monopoly (Ehret 2008). The eventual publishing and effective "open sourcing" of that knowledge not only led to general access to local tidal conditions, but a global understanding of tidal function.

Thomas Jefferson was known to have personally smuggled in his pockets rice varieties from Italy that are now grown in the Southeastern United States (Mazzei 1975). Jefferson believed that favorable genetics were part of the global commons, and it was not a crime to "liberate" the seed for establishment elsewhere; he also wrote disparagingly about those who attempted to restrict the best genetics of sheep to extract a top price, and schemed to instead offer the best rams at cost to improve flocks across the United States (Jefferson, 1810). The well-known industrialist, Francis Cabot Lowell, smuggled knowledge of British power looms by memorizing their designs. More optimistically, open source projects illustrate, just as in nature, that competition is only one factor in evolutionary success. Cooperation, coevolution, and symbiosis are also evolutionary strategies. In 2014, the electric car company Tesla provided a contemporary high profile example with the announcement that it would not enforce patents, and even invited the use of its technology by competitors. Disrupting the knowledge ecosystem through open sourcing key knowledge or technology is a strategy designed to shift the competitive landscape in conditions of mismatched/asymmetrical entities of scale and political power.

The segmentation and restriction of knowledge in agricultural research and development, through protection and specialization, has led to imperfect knowledge in markets and has contributed to market failures. Current externalities have established beneficiaries, with market power that provides an incentive to keep external costs from being valued. A hegemonic cultural situation will work to reduce change by creating deliberate barriers to entry to slow change and benefit the status quo. The resulting externalities are a byproduct of the dominant culture that cannot be solved with a simple technical fix. However, technology, especially technology that is collaborative and community based, is a means to bend and change the cultural biases past the "K" conservation phase, described in Chapter 2, and move gently into a new adaptive cycle.

Because sustainability itself is a social construct, and not simply a technical or biological challenge, a systems based approach is needed to provide wider internalization of biological function with cultural and environmental service values. Of primary importance is that underlying environmental mechanisms and values are incorporated into the dominant culture, otherwise negative externalities will expand and efficient markets will be elusive regardless of technical capability. Open source communities and the products and community generated by them, such as networked sensors, low cost UAVs, and a mobile, socially networked population, symbolize and make possible a shift to a less hegemonic and more engaged culture of scientific research.

The common theme of each of these four movements (physiocracy, agrarianism, ecological economics and open source community) is the importance placed on the free flow of knowledge. The open source software which now runs the Internet is the modern version of the enlightenment's intellectual commons. Jefferson's vision of agriculture was also one that envisioned an ever expanding intellectual commons. As a member of the "society of letters," he was a contributor to the *Encyclopédie.* He was eager to try promising innovation in farming and, if the experiment succeeded, to share the benefits with others. Thomas Jefferson wrote to then President Madison, referencing the deliberate restriction of the Merino sheep genetics by speculators.

> "No sentiment is more acknowledged in the family of Agriculturalists than that the few who can afford it should incur the risk and expense of all new improvements, and give the benefit freely to the many of more restricted circumstances. ... I will throw out a first idea, to be modified or postponed to whatever you shall think better. ("Jefferson, 1810)"

He then went on to propose a method to "open source" and distribute the best quality genetics across the countryside for the benefit of the republic. A culture that values and is motivated by the exchange of knowledge would also have open source tendencies. The open source software communities are particularly dominant within the networked software culture of well-known communities such as Apache and Mozilla. These strong tendencies also overlap with agriculturalist ideals, and share biological metaphors to explain the exchange of knowledge (circulatory system) or the structure of networks (neural networks). Francois Quesnay, was a physician prior to becoming an influential economist, and was best known for proposing that blood did not terminate at the limbs, but circulated through the heart. It was this insight that he applied to political economy and agriculture (and nutrients) across a landscape.

Given that a limiting factor in effective participatory research is likely cultural, it is interesting to consider that it was not until industrialization, around 1840, that the concept of the professional scientist emerged, well after the Enlightenment (Ross 1962). Prior to that time the pursuit of science was called Natural Philosophy and provided the basis for the Industrial Revolution and future scientific discovery. The transition to the adoption of the term “scientist” (as in “artist”) emerged as a term along with industrialism and professionalism of science, which overshadowed science’s social role in creating a more informed public. This transition also followed a transition from a focus on inductive learning, or learning from observation with an assumption of uncertainty, to a focus on deductive learning, or learning based on assumptions of certainty which became possible with the accumulation of scientific discovery. The specialization and focus on deductive approaches emerged from the classification of disciplines over the next hundred years resulted in great scientific advances, but at the cost of creating a cultural gap between scientists and other members of society. The consequences of professionalization, from a cultural perspective, was the marginalization of general inquiry and amateur observation. The tension and social aspects of the deductive and inductive methods are covered in Chapter 2.

Early 20th century agrarians, partly in reaction to industrialization, built upon the enlightenment ideals of the 1750s Systematic Dictionary of the Sciences, Arts, and Crafts represented in the publishing of “Farm Knowledge: An Encyclopedia of Practical Knowledge.” Published in 1918, it was distributed through the most modern distribution method of the day – the Sears’ Catalog. The 640-page text of this encyclopedia has been digitized (at a cost of less than $200) and archived by this author at www.archive.org, and it is editable in wiki format at www.farmhack.net. Open source communities and the creation of collaborative platforms like wikis have also made a new, flatter, more participatory model possible.

Agricultural systems communication has always been challenging because of the biological, cultural and economic variables unique to each application. The agri***culture*** of sharing knowledge, and how it is shared, also vary widely. The traditional approach to that complexity has been direct observation with farmer-to-farmer social contact, supplemented with extension (a concept proposed by Mirabeau and echoed by Jefferson in the creation of the University of Virginia) and professional services (Joseph and Andrew 2008; van de Fliert and Braun 2002). “Farm Knowledge” was yet another attempt to aggregate practical knowledge to enable accumulated knowledge to exchange across a landscape in printed form. Just as Quisney did a century and a half earlier, the encyclopedia itself describes a natural metaphor of the circulatory system of knowledge and observations, transferring both information and inspiration. Figure 40 captures the mixing of knowledge, labor, biology, and the creation of feedback through the social exchange of systems observations at agricultural community clubs.

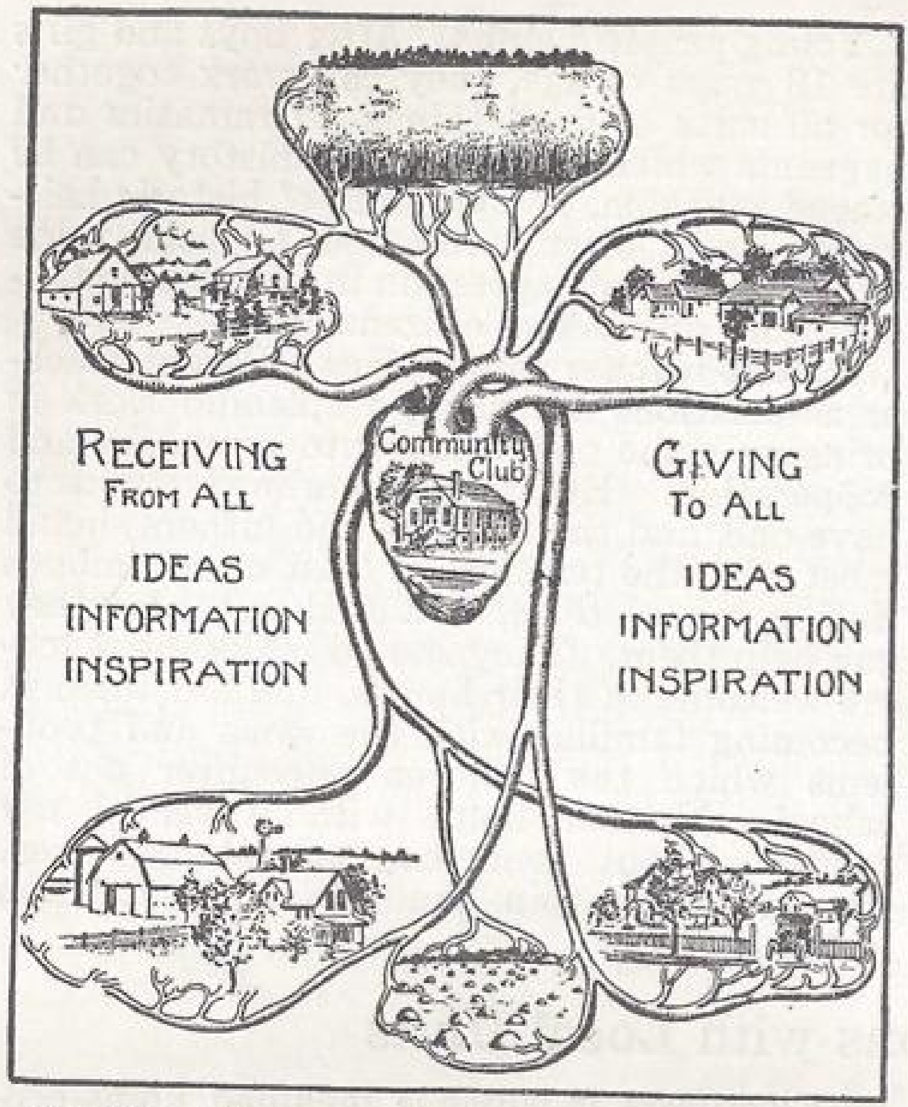


FIG. 281. The community club, rightly organized and conducted, can serve as the heart of the community through and by which a stream of inspiration and encouragement is sent to every member.

Figure 32 – The Community Club knowledge exchange from the Encyclopedia of Practical Farm Knowledge (Seymour 1918). **This figure illustrates both the extension of a biological metaphor to describe a circulatory system of knowledge, as well as the culture of sharing that extends beyond the information, and also the inspiration that comes from social gatherings and explorations and experimentation.**

The community club structure and the natural metaphor of the circulatory system effectively communicates that the limiting factor in the successful adoption of beneficial practices is not natural resources, but culture, and a culture that produced access to continually appropriate feedback and knowledge. Brekelbaum (1990, 1994) conducted a literature review of self-reliant and self-managed projects and identified various essential skills for farmers, including a list of criteria for success that looks, unsurprisingly, like the characteristics for general resilience and adaptive systems (Walker and Salt 2006).

The essential skills included: (brackets for relevant resilience framework reference)
• Critical thinking (**feedback loops**)
• Diagnosing and solving problems (**systems understanding**)
• Formulating and prioritizing objectives (**systems dynamics**)
• Developing and implementing action plans (**adaptive governance**)
• Systematizing information and analyzing results critically (**systems dynamics and understanding**)
• Identifying indicators for quantitative and qualitative monitoring and evaluation (**feedback loops**)
• Developing external linkages, both horizontal and vertical (**substitutability and modularity**)
• Showing solidarity (van de Fliert and Braun 2002) (**reserves**)

The community club model for exchanging ideas is particularly effective, and extends beyond any single element of the system. On a local level feedback can be quite rapid. However, the feedback is limited to the quality and quantity of the observations within that location.

The technical accomplishments discussed earlier make the sharing of systems observation possible across broader spatial and temporal scales. The exchange can happen in the form of on-line videos, wikis, forum comments and more structured data exchange (Silvertown 2009). However, the building of trust and community, although different, is just as critical within the on-line community as within the local agricultural/community club model. Farm Hack, discussed in later case studies, in particular has tried to merge the two, with implementing local meet-ups called "Farm Hacks", design charettes or "hackathons" with a strong emphasis on the socializing and sharing of food with knowledge exchange and technical problem solving, followed up with on-line documentation and communication. During the course of this study the sophistication of the on-line collaborative tools evolved significantly. In the first iterations, Farm Hack used collaborative tools that enable simultaneous editing and sharing across communities, like Google documents, followed by similar open source and ether-pad based tools like hackpad.com. Most recently, Farm Hack has added project Kanban boards, such as Trello, that are typical in Agile software development, and that enable multiple users to contribute ideas, vote on priorities, and simultaneously edit documents. These on-line tools mimic in-person collaborative processes. They also facilitate building trust through a balance of transparency in the collaborative process and also control of publishing and editing rights within the community. Google Hangout, and similar tools have also become crucial tools for remote collaboration and project status updates. The video element and informality of the process builds community through active widely attended screen sharing and video conferencing sessions. A weekly video check-in for the volunteer software development team can often have more than six participants. The informal nature of the video conferences has resulted in food and beverages being displayed and consumed to "share" with others.

The entry about agricultural clubs within the *Encyclopedia of Practical Farm Knowledge* mentions that at every gathering food would always served as part of the ritual(Seymour 1918). That same importance of food in community building has been adopted at in-person "hackathon" and contemporary GreenStart and Farm Hack events discussed in Chapter 7 case based studies. Food and socializing is not viewed as peripheral, but a central part of building trust within the sharing and learning community. The community generated Farm Hack "event" tool wiki captures additional elements that are important based on observations and feedback from each event. Creating and extending social commitment and trust within a group is harder on-line, but equally important. Similar cultural patterns emerge around Public Lab events and BioBlitzes and represent examples of the mixing of in-person social events with participatory science and R&D (Cohn 2008; Clements 2013; Michael 1998; Devictor, Whittaker, and Beltrame 2010; Irwin 2001; Cooper et al. 2007; Newman et al. 2010; Bonney et al. 2009; Newman et al. 2012).

Open Source Agriculture and Social Media

The heart metaphor illustrated in the *Encyclopedia of Practical Farm Knowledge* illustrates the same operating principles that are embodied within the structure that are being carried on within the organizations explored in case studies covered in Part II of this dissertation. These communities were formed in part to address, within a 21st century context, many of the same biological, economic and cultural ideals, and political economic failures that motivated earlier agrarian and Physiocratic movements. Contemporary organizations are able to employ many of the same methods to create a "circulatory system" of ideas that spreads inspiration and innovation at the local and community of exchange, but also can extend the reach much further and faster through collaborative information technology now available. These organizations follow a "network" centric approach, rather than traditional non-profit structures, and follow design principles of distributed economics and subsidiarity which specify that structures should not be larger than they need to be to function. Chapter 7 covers network based organizations and the collective impact approach as part of the case based analysis. The network based minimalist approach was implemented not only by design but also of necessity due to the low budgets indicative of community based organizations operating outside of the power structure and the administrative overhead and distributed nature of technical and social linkages that hold the structures together.

The strength of the networked approach is resilience, adaptability and low overhead. These strengths make a networked organization a good fit for adaptive management and applied inductive research that is constantly adjusting to feedbacks and building on past case based learning. The weakness is that in isolation, and without participation, there is little replication or external feedback, and observations are difficult to validate without a larger context that comes from a functioning network. Networked adaptive management, however, makes individual observations more meaningful by placing the observations in a broader context. By enabling data sharing of on site (*in situ)* observations, additional technical, social, biological, interactions that cannot be controlled for or replicated in isolation can also be captured and included in broader systems study and analysis. The additional benefit of networked participatory action in adaptive management is that *popular* agronomy (i.e., avocational interest and study) and greater biogeochemical literacy is a byproduct that also achieves science's social objective of a more informed public. Charles Darwin, also a product of the Enlightenment and an inductive observational scientist, insisted on the importance of writing for the public. "I sometimes think," he affirmed, "that general and popular Treatises are almost as important for the progress of science as original work" (Lightman 2009).

Darwin's insistence on general accessibility of scientific inquiry supports the Physiocratic social model that general "popular" inquiry is as important as original work, and from a holistic perspective that low science literacy of a population is an indication of a cultural failure in the practice of science.

The development of new measurement tools can have a profound effect not just on the direction of scientific inquiry, but on who can ask questions, how science is funded, and who participates. All are an expression of cultural values and the value placed on the natural and intellectual commons. The effect of observation tools on human values about the environment has been well documented in the cultural history of the telescope in placing the Earth and humanity within the context of a solar system, and the microscope and x-rays in exploring the structure of our bodies and our environment, and more recently satellite images of the planet that helped spark the environmental movement (Sagan 2006).

Geographic data sharing has become popularized through remote sensing images now available through Google Earth. New low cost aerial imagery has enabled scientists and citizens alike to view the local environment from a different perspective both literally and figuratively. Observational tools, and access to data stored from those observations also shift the dynamic balance between the advantages of inductive vs. deductive scientific approaches.

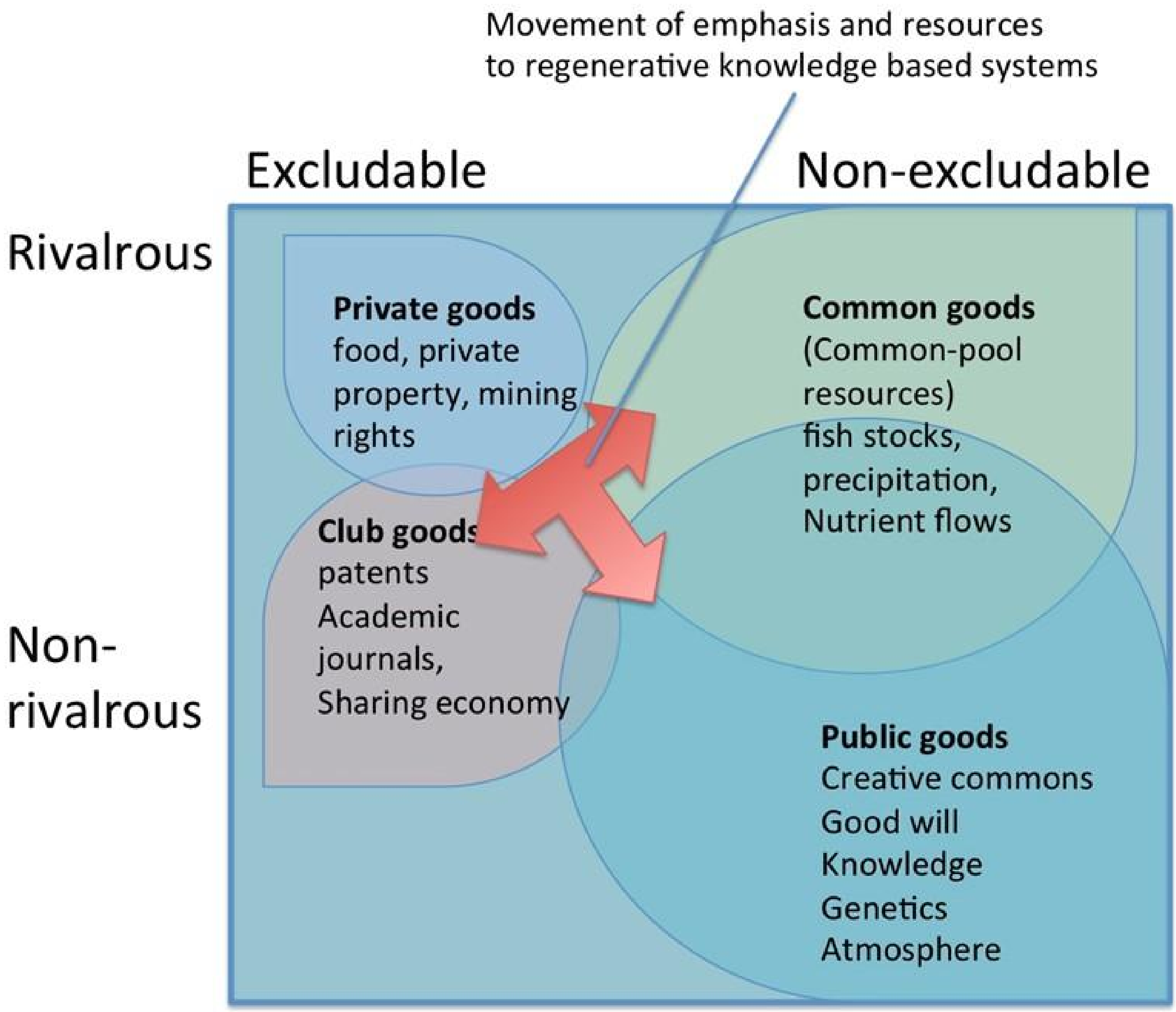


Figure 33- A knowledge based system creates incentives for expansion of public goods. The basis of economic growth and wellbeing is tied to the productivity of regenerative common resources and the cycling of nutrients (e.g. water, carbon, nitrogen, phosphorus) through plants and soil. This contrasts to extractive systems and world views which tend towards a vision of scarce finite resources that therefore need to be protected through the exertion of force (market or otherwise)(Meadows and Meadows 2007)**.**

The Physiocratic framework approach reemphasizes public goods and the relationship of public goods and commons management that can still foster profitable healthy private enterprises. Public knowledge of environmental systems and best management practices and a learning culture are non-rivalrous, non-excludable goods.   They can be used to create a more productive commons that supports a regenerative basis for private goods - rather than private goods only generated from the production of more private goods.

The historic tension between inductive and deductive approaches to research is especially relevant to this study due to the social implications of scientific knowledge being treated as a public good or as private property. The change in the accessibility, cost, and ubiquity of tools to communicate and observe our environment shifts basic assumptions about the historic advantages and disadvantages of the approaches. The accessibility of systems approaches and inductive methods that are already more common in ecology and healthcare, provide a complimentary context for an alternative to reductionist and proprietary models of inquiry.

Reductionist Research and Extraction

The reductionist approach to inquiry and questioning has been necessary partly because of the high processing cost and the associated complexity of exploring unknown interactions. As already illustrated through global ecosystem service market failures, the over-focus on deductive inquiry and resulting “siloed” specialized knowledge has had unintended negative social and economic effects. Segmented, specialized knowledge and the creation of professional expertise as intellectual property paralleled the development of extractive systems in agriculture, energy, and mining. These approaches and methods have been the engines of the global industrial economy, and have led to greater efficiency in the extraction of resources at greater rates. However, because of the limitations of deductive approaches applied to systems and the inability to manage experimental complexity in place, the result has been an oversimplification of agricultural processes and the creation of associated externalities. Social costs associated with an overreliance on deductive methods include concentrated knowledge and wealth that relates to agricultural practices that *do not* lead to cultural internalization of the biogeochemical systems understanding. Total productivity of the biosphere, and public knowledge of its function, should be held in the commons as part of science's social mission to create a more informed public. Examples of detrimental oversimplification of systems study can be seen in the recent documentation of plant available organic nitrogen, the variety of fungal communities within healthy soil, and nitrogen producing bacteria within non-legume soil aggregates, all of which were missed or dismissed until they were studied in place (M. F. Allen 2007). Laboratory methods, in an attempt to isolate and simplify conditions, served to destroy the complex environmental conditions required for the processes and population function to be properly observe (Seiter, Ingham, and William 1999). Problematically, deductive research methods form a "cleaner" cultural fit for resource extraction, and specialized corporate and academic funding processes that tend to reward products (e.g., mineral yield, crop yield, papers published) over outcomes (e.g., improved biogeochemical literacy, and expanded soil function and net primary productivity).

The dominant paradigm of the last part of the 20th century treated knowledge as intellectual property, essentially a private fixed resource to be monetized as a method of value extraction. This paradigm is evident in the proliferation of NDA (non-disclosure agreements) patent suits in the technology field. One of the symptoms of this reductionist approach, which depends on specialized professionalized inquiry rather than broad participatory questioning, is that much of the knowledge gained is inaccessible to farmers and the general public, as well as to scientists in other academic fields; often, research is accessible only behind academic or commercial paywalls (Willinsky 2010; von Krogh and Spaeth 2007). This view of knowledge as a scarce resource, as *intellectual property*, parallels natural resource economic models that treat nature in general, and soil in particular, as fixed assets to be measured in value by their extraction efficiency, rather than as part of a global commons that can *appreciate* with proper management. The role of soil in the carbon, nitrogen, phosphorus, and water cycles is an example of both stock and dynamic flow that varies with management. The dynamic nature of these flows, and imperfect flows of knowledge, have led to the market failures already discussed.

With advances in communication technology beyond the printed page and analog telephone lines, the cost of storing and exchanging data and knowledge has dropped, making protecting data more difficult now than sharing it (Huang et al. 2014). Because of these techno-sociological changes, adaptive management, as described within this study, is moving within the reach of applied science. Computationally intensive approaches now cost little enough, and provide high enough resolution, that fast changing nutrient cycles, soil health, water quality, pathogen, and population patterns can be modeled and used to provide management feedback. Examples of landscape and watershed models for nutrient cycling such as AdaptN and DNDC illustrate that it is now possible to model with enough accuracy to make environmental management decisions (Van Es and Degaetano 2008; Li et al. 2012; Giltrap, Li, and Saggar 2010). These types of sophisticated models, which can be run on consumer hardware and/or over the Internet, illustrate the potential to expand what questions can be asked, who asks them, and how they are funded beyond the realm of universities, government and corporate labs. The changes in assumptions about the research process and the cultural application of scientific knowledge opens the potential for alternative approaches which link conventional deductive methods with participatory inductive approaches through open source software and research and development practices.

Inductive Participatory Research

The social technical framework proposed by this dissertation builds upon the benefits and limitations identified within the maturing field of participatory research. It is based on the observation that farmers, professional scientists, and citizen researchers have different knowledge and skills (coming from different parts within Mirabeau's Tree), and that these may complement each other. Through collaboration, the many groups may achieve better results than by working alone. Most academic agricultural literature focuses on a formal managed process for research. A broader review identifies examples of network, systems based and technologically-facilitated processes that rely on a more open approach for participation as well as organization.

The following statement articulates that a collective action approach is particularly effective for complex social and systemic challenges:

> "The solutions we have come to expect in the social sector often involve discrete programs that address a social problem through a carefully worked out theory of change, relying on incremental resources from funders, and ideally supported by an evaluation that attributes to the program the impact achieved. Once proven, these solutions can scale up by spreading to other organizations. The problem is that such predetermined solutions rarely work under conditions of complexity—conditions that apply to most major social problems—when the unpredictable interactions of multiple players determine the outcomes. And even when successful interventions are found, adoption spreads very gradually, if it spreads at all. Collective impact works differently. The process and results of collective impact are emergent rather than predetermined, the necessary resources and innovations often already exist but have not yet been recognized, learning is continuous, and adoption happens simultaneously among many different organizations. In other words, collective impact is not merely a new process that supports the same social sector solutions but an entirely different model of social progress."(J. Kania and Kramer 2013)

Collective impact methodology is being used as the basis for the local food system organizations examined as case studies in Chapter 7. These are social rather than biological systems, managed using an adaptive management approach under another name. The same principles also parallel the "agile" software development methodology previously discussed. The application of these principles through case studies in Chapter 10-12 will illustrate examples of the complementary and crucial supporting role that researchers using deductive science play in building a cutting edge participatory research system.

Participatory research projects have often created limited practical cooperation between farmers and scientists, mainly because the strengths of farmers and the limitations of researchers are often overlooked; as a result, the communication and interaction between the two remains superficial. Emerging technology illustrates that these limitations can be overcome. Hoffmann (2007) proposed that it is crucial to first recognize farmers' achievements, and then focus on five steps towards optimizing collaboration for rural innovation:

1. more user orientation
2. more decentralized dissemination of research and results
3. openness towards informal modes of experimentation
4. more externalization of tacit knowledge
5. more respect for farmers' opportunity costs

(Hoffmann, Probst, and Christinck 2007).

These five steps are embodied by the applied case studies covered later in this chapter as well as within the proposed Physiocratic framework for adaptive management and participatory research and development.

Locating research on farms is essential for studies involving 1) management histories and physical conditions not available on experiment stations; 2) farmer management, especially of innovative systems; and 3) ecological effects of whole-farm changes
(M. D. Anderson 1992).

These three criteria identified by Anderson are the conditions met by any farm attempting adaptive management, and therefore support the need for participatory research and development methods. The Physiocratic framework proposed within this dissertation and the manifestations of the framework covered in Chapter 7 (Farm Hack, Public Lab, Ecosynq and GreenStart) provide applied examples. The benefits of participatory research that involve farmers and citizens produces advantages in the design, implementation, and dissemination stages of research and development (M. D. Anderson 1992). Anderson continues:

> "These benefits may warrant locating a project on a farm even if it could also be done on-station. Misunderstandings about the value of on-farm research are often due to its promotion in conjunction with sustainable agriculture and greater political power for farmers. On-farm research, especially with high farmer involvement, is more appropriate for answering some questions critical to developing more sustainable agricultural systems; but other aspects of sustainable agriculture are more suitably studied at experiment station sites. Greater involvement of farmers in all stages of a project is conducive to improving communication and cooperation with agricultural researchers and administrators. However, not all research on farms should have this kind of farmer involvement; and simply increasing the amount of on-farm research does not necessarily augment farmers' political power (M. D. Anderson 1992)."

In addition to the farmer and citizen based case studies presented in Part Two, other studies have found that improving agricultural sustainability requires holistic and integrated strategies that are relevant and legitimate at the local level (Keeney et al. 1999; W. Allen, Kilvington, and Horn 2002; Leeuwis, C. Pyburn 2002). These examples provide a complementary approach to governmental based use of a combination of extension and subsidies, which according to Vanclay and Lockie (1995) are now considered poorly suited to the challenges posed by sustainable agriculture. However, governments turning to participatory research approaches face challenges of local legitimacy and establishing local trust. Leveraging the potential for participatory research in sustainable agriculture requires first an understanding of the nature and purpose of participatory approaches, as well as of the methods necessary for building on-line and local communities necessary for success (Bruges and Smith 2007).

Bruges and Smith (2007) continue:

> "Even the most fervent proponents of participatory approaches have come to realize that participatory research should be presented as complementary to conventional research. In a maturing field of

> participatory approaches there is an emerging group that call for 'uniting science and participation' and emphasize the 'comparative advantages of farmers and scientists' in generating knowledge and innovations and propose innovative ways to combine 'local and global science'."

In a similar vein, Rhoades and Nazarea (2006) suggest that "what local communities demand is not necessarily a choice between 'participation' and 'formal research', but a new, mature relationship with outside agencies and individuals." These positions reflect the many new approaches made possible with communications technology that combine various forms of stakeholder participation with cutting-edge scientific research. An adaptive framework for participatory agricultural research will enable projects to take into account the increasing diversity and multi-dimensional character of sustainable agriculture, food security, and natural resource management.

Many analysts and practitioners of participatory research identify different levels and forms of participation in research that can be structured by specific typologies. Most of these research approaches have their roots in an early classification of different degrees of citizen participation developed by Arnstein (1969). The "participation ladder" recognizes categories ranging from manipulation (classified as non-participation) to consultation (described as a kind of tokenism) to citizen control (considered as the highest degree of citizen participation). The disadvantage of this approach is that the structural values assigned to each level give an impression that they are in some rank or order, rather than seeing each type of inquiry as a complementary part of a healthy learning community. Probst et al. (2003) determined key variables of a combination of four approaches, namely:

(1) **transfer of technology** (formal research without substantial

farmers' participation)
(2) **supply-on-demand** (formal research where farmers have control over own or donated research funds)
(3) **farmers first** (where farmers participate in the generation, testing, and evaluation of technology)
(4) **participatory learning and action research** (innovation is considered to be the outcome of a mutual learning process amongst a multiplicity of actors and networks)
(van de Fliert and Braun 2002; Probst and Hagmann 2003)

This focus on approaches highlights different research strategies and their underlying philosophies, and provides a context for the case studies used in Parts Two and Three. These approaches are more flexible than rigid classifications; however, the identification and listing helps to sharpen the differences between the approaches, and brings more conceptual clarity into the discussion. Implicit with this structure is the understanding that projects can change over time, spread geographically, and proceed along different paths within different communities. ‘‘Participatory learning and action'' types of research projects might involve farmers during the whole process of technology generation, while the dissemination of the technology by local extension workers may follow a classical ‘‘transfer-of-technology'' approach. Research projects may also have certain features that would classify them as ‘‘farmers first,'' whereas other features would correspond more to the ‘‘supply-on-demand'' type.

GreenStart and Farm Hack, profiled in Chapter 7, emerged within the context of attempting to support participatory inquiry methods, but also with an understanding of traditional technology transfer. Open source projects in agriculture, although historically not a new idea (as evidenced by the Physocratic movement), are a relatively new phenomenon to the contemporary literature. New tools such as Farm Hack will enable more quantitative tracking of the velocity of technological transfer through the automatic logging and archiving of all contributions and posts by community members. The global trends in open source projects, which could be seen as a reasonable projection for agriculture, grew from just tens of thousands in 2006 to over a million projects in 2012, and the number of projects is projected to double by 2014 ("The Eighth Annual Future of Open Source Survey | Black Duck," 2014). Chapter 7 provides examples of these structures that represent part of the open source trajectory.

Chapter 7: Application of a Physiocratic Framework: Case Based Studies

Chapter Introduction: Prodding the System

As discussed in Chapter 6, complex interactions of biological, technical, and social factors are still poorly understood and therefore favor inductive approaches for analysis to form the basis of theory development. A case based study approach provides a good fit to build observational and interdisciplinary systems frameworks. In practice, the methods used in the following case studies draw on approaches often referred to as "action research," "learning by doing," or "lessons from practice." Figure 34 illustrates the different niches that the case studies chosen for this study occupy. Each of these organizations in their niches use environmental data with different goals, but the techniques for gathering it and exchanging it are similar. Figure 35 expands on Figure 34 and positions the case study organizations within Mirabeau's Tree to illustrate the relationship of the organizations to broader social systems, and relate the data collected and exchanged by the organizations to the broader structure. In Figure 35, Daly's Pyramid is juxtaposed to illustrate the similarity in structure to Mirabeau's Tree. The ultimate means are the tied to the organizations acting on the natural resources (Soil Health Initiative), while the organizations at the top (Food Solutions New England) are working on the ultimate ends by influencing social behavior and values through network development and policy that reflect on behavior throughout the system.

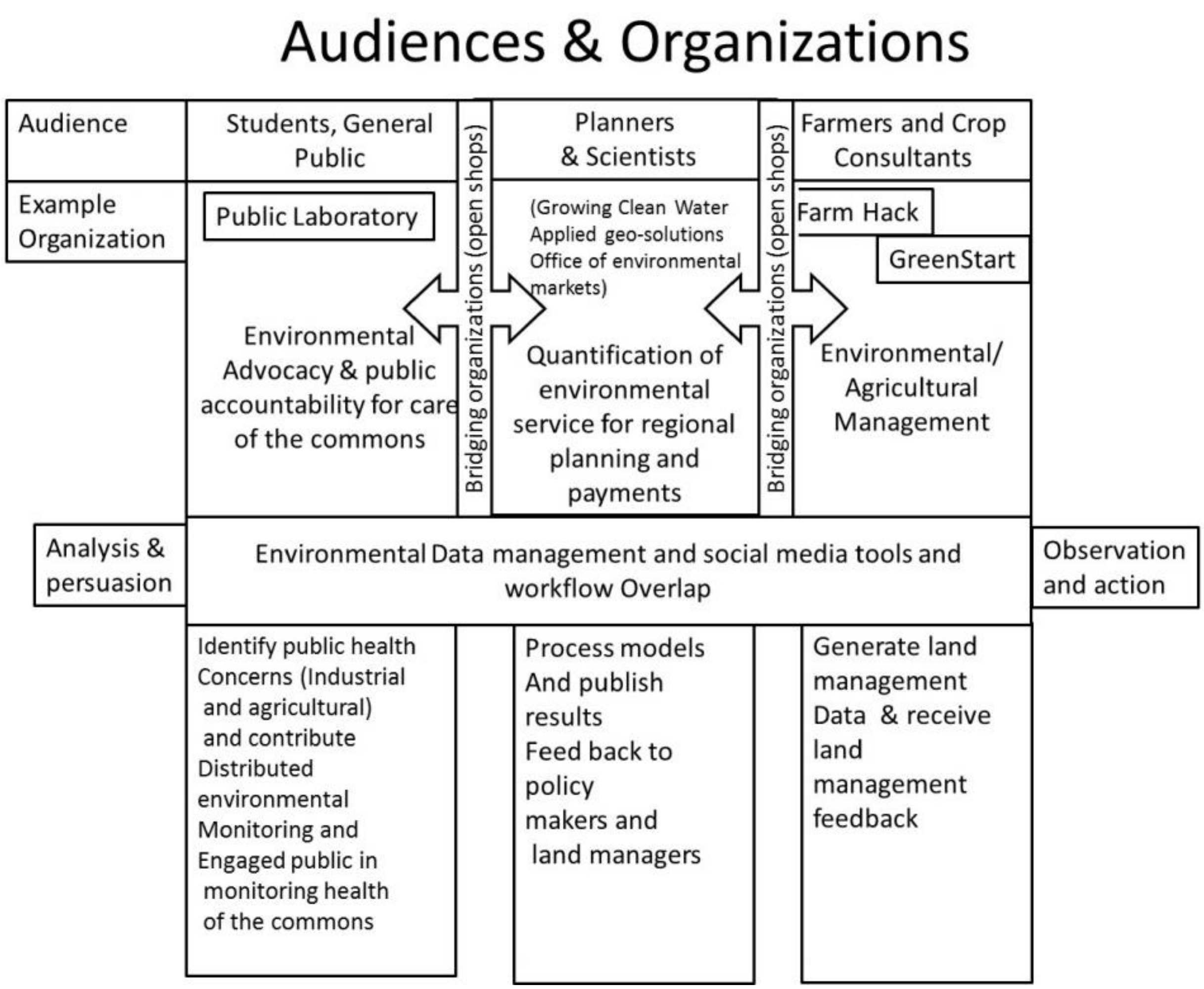


Figure 34 – Functional locations of case studies within the Physiocratic framework. The case studies used (example organizations) for this study are similar in their use of data for adaptive management goals, but occupy

different functional locations within the Physiocratic framework. Farm Hack and GreenStart are closer to the roots, and Public Lab, as an advocacy organization, is located in the canopy of the tree. The organizations on the left are observational and geared toward citizen education and policy, while the ones on the right are more action oriented towards environmental management. This diagram illustrates the organizational relationships of data collection, analysis and action and the flow of data across organizations, as well as how these relationships are complementary and important to whole systems study.

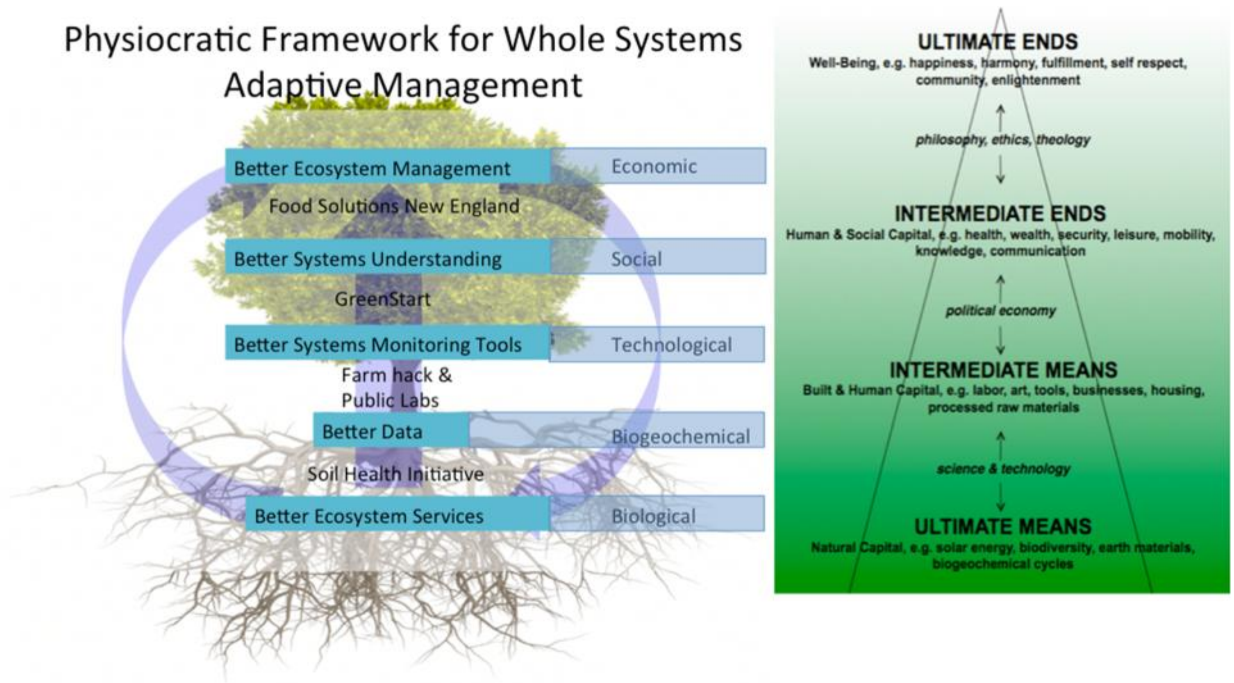


Figure 35 – Each of the case studies is further positioned relative to both Mirabeau's Tree and Daly's Pyramid, to illustrate the breadth and coverage of the examples chose to study and the relationship of organizations to their function within the system. For example, the Soil Health Initiative is focused on the root of the system (Mirabeau) and also addressing the ultimate means (Daly). This contrasts with the Food Solutions New England case study, which is focused almost entirely on the outcome and social means to achieving food justice and equity as an output of Mirabeau's Tree and at the top of the pyramid as ultimate ends (Daly).

Case Study One: GreenStart

Methods

The GreenStart case study used an approach of studying action within a system through the application of the Physiocratic framework to an organization to test the social, biological, and technical systems reaction to those actions. GreenStart was founded to create local examples and to remove barriers to agricultural experimentation and the exchange of agricultural knowledge and innovation. It is highlighted as a case study to illustrate the particular application of a networked organization modeled on the Physiocratic framework.

> "We have dwelt on this subject because it is of great importance to mankind. We invite those whose wealth permits them to undertake costly experiments with no guarantee of success, yet without incurring any financial hardship, to add the weight of experiment to the parallels and conjectures made by M. Duhamel. This skillful academician wisely judged that one small example would have more impact than reasonings which, though sound, would not be understood by most men or trusted by those who might have difficulty in following them. (Diderot 1751)"

Diderot's observation of Jethro Tull's work over 250 years ago illustrates the importance of local examples to encourage further experimentation. Observation of human behavior forms the historic background for GreenStart's approach to applied agricultural examples and experiential learning. In this way, GreenStart has applied the basic Physiocratic model to its operation, but updating the method with current tools for participatory action research and collaborative adaptive management (CAM).

Although not explicit at the time of its founding, GreenStart became an experiment to test an alternative organizational structures and Physiocratic ideals. The author's role in the experimental organization and transition was first as a founding board member, and then the executive director. Both roles provided in-depth access to the operations and interactions of the organization. The author observed the results through years of informal interviews and interactions with other organizations, farmers and researchers that created an emerging agrarian network. The case study below is based on the first hand observations of GreenStart's operation, its context and function.

Overview: A Regional Agrarian Social Club for Knowledge Exchange

GreenStart was formed in 2006 as a non-profit to share agricultural innovation, and has incorporated many of the characteristics of resilience, open source community, and agrarianism into its structure and mission. The structure and language of the organization illustrate ties with its historic agrarian roots and the Physiocratic framework identified in Chapter 2. GreenStart's evolution in many ways paralleled the exploration and development of this study. When GreenStart was founded, the organization had a fairly narrow focus on biodiesel availability and use in New Hampshire. As the study progressed, its focus shifted towards a broader Physiocratic understanding that moved GreenStart's agenda towards the larger agrarian value of soil health. By March 2010, GreenStart had adopted the following mission and laid out the groundwork for an applied case study for the Physiocratic framework and participatory research called for by Jethro Tull 200 years earlier: "To foster a resilient energy and food system for New Hampshire by providing technical education and practical agricultural examples."

Although GreenStart does not publically reference the Physiocratic framework, GreenStart's web site reflects Physiocratic ideals in practice. For example, the web site states that "GreenStart sees food and fuel security as the end-product of a vibrant, sustainable agriculture system in New Hampshire." This statement places the organization in an agrarian context, and makes the Physiocratic link to soil and free knowledge exchange more explicit by going into more detail:

> To achieve this end, GreenStart facilitates projects that
>
> 1) Increase soil carbon "banking"

2) Decrease energy inputs

3) Increase both food and fuel outputs (positive energy and carbon balance)

4) Promote "tight" cycling of nutrients

5) Provide open source access to appropriate knowledge, seeds, and equipment"

GreenStart positions itself as an organizational experiment to test innovative approaches to both land management, participatory research, and communication of science. It describes itself as practice-based to provide functioning local examples of agricultural practices that are critical to adoption of new technology, building active on-farm projects, and promoting on-farm research.

GreenStart partners with institutions, but can adapt quickly and stay focused on results in the field. GreenStart works with academic institutions, regulatory agencies, NGOs, landowners, and farmers to fill practical "gaps" in knowledge or equipment; partners include UNH Cooperative Extension, USDA/NRCS, NHACD, County Conservation Districts, Cornell Soil Health lab, and individual farms across the state and region. In line with Darwin's observations about the importance of publicly accessible science (Lightman 2009), GreenStart promotes the concept of "Popular Agronomy" (As in Popular Science/science for non-scientists or those working in avocational science) and provides tools for producers to work towards continuous improvement through on-site research.

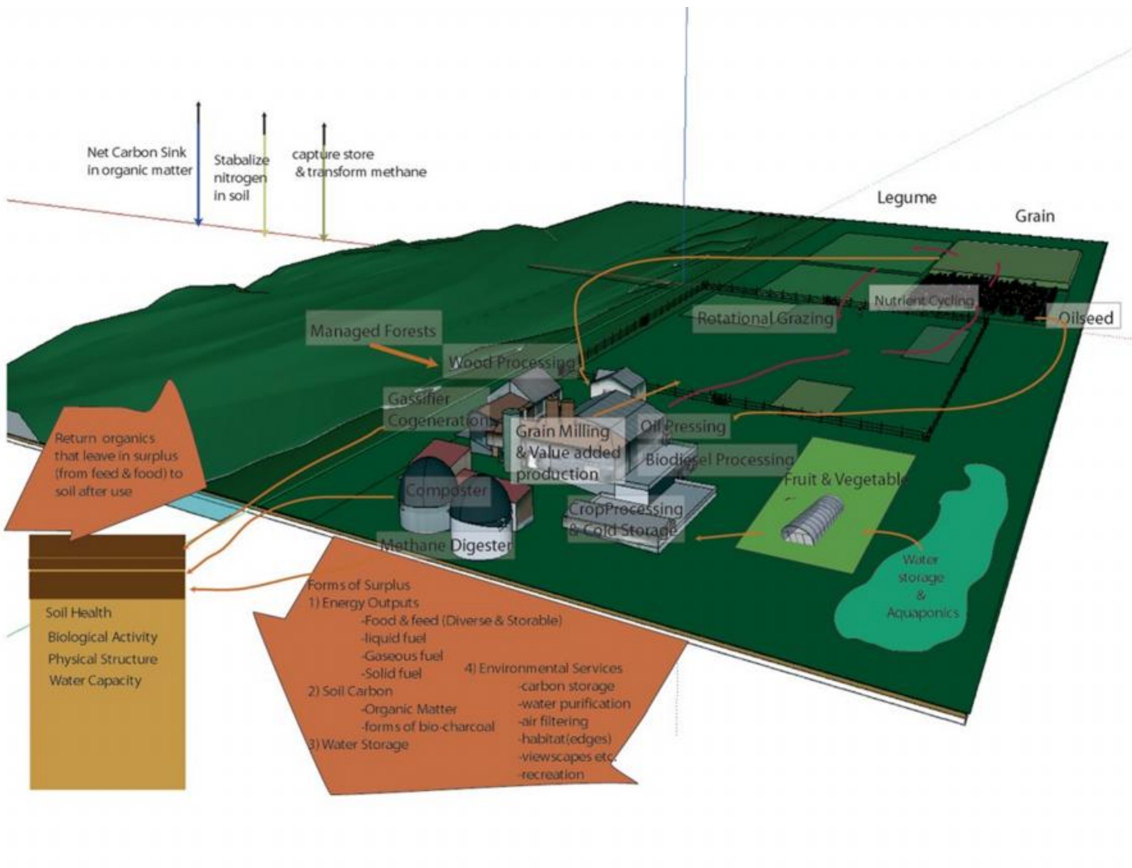


Figure 36 – A systems based landscape model was used as the foundation of GreenStart's work, and created a static draft for the actual nutrient modeling, landscape documentation, and networked sensor work and visualization software that became possible through the development of open source hardware and software projects.

GreenStart's own description reflects not just contemporary adaptations of Physiocratic social principles, but also an updated version of the Enlightenment-era salon and the early 20th century agrarian agricultural club, geared toward inspiration and innovation shared by all. Unlike its historic counterparts, GreenStart benefits from social communication technology that can facilitate collective action towards systematic transition to valuation of agro-ecological systems. The social communications technology has made it possible to be organized without an elaborate or hierarchical structure. GreenStart's network-based model also tests this concept.

Outcome and expression within the system:

In practice, the networked organizational structure of GreenStart relies on partnerships and coordination with more established existing entities such as NRCS, NHACD, Cornell University, and UNH Cooperative Extension to disseminate relevant on-the-ground information. Open communication and coordination of projects does not eliminate the need for an organization entirely, but greatly expands and leverages existing organizations and enables recombination of them to create an organized approach. To illustrate this, the following section will present GreenStart projects and accomplishments with a budget that supported only one to two part-time paid positions at any one time.

GreenStart's projects have included the development of a statewide, voluntary, innovative farmer network by working closely with and providing technical support through conservation districts in all ten counties of New Hampshire. This participatory network has demonstrated cover crops, as well as developed, tested, and demonstrated new equipment and enterprise models. GreenStart programing has also developed on-farm energy systems such as the modular open source mobile biodiesel processor documented on FarmHack.net. GreenStart has promoted a strong soil health initiative, and assisted with technical capacity building of New Hampshire farmer, and facilitated equipment lending programs around the state. The network has been built in coordination with many local and regional partners.

More than twenty farms in four counties participate in GreenStart's network developing long term soil health management plans in cooperation with the Cornell Soil Health Lab, Conservation Districts, UNH Cooperative Extension and the USDA/NRCS. The original network of farms now extends well beyond the twenty farms in all ten counties, with stronger relationships building directly from farmer-to-farmer exchanges over soil health, covercrops, silvopasture and nutrient management being key drivers.

In 2013, at least twenty farmers attended each of five no-till and reduced energy agricultural workshops in four counties representing tens of thousands of acres under farmers' management. Subsequent to GreenStart's work, at least five conservation districts have developed equipment sharing programs to assist with no-till and soil health practices, based on technical expertise provided by GreenStart. Hundreds of farmers participated in workshops presenting the Cornell Soil Health analysis and its role in measuring on-farm energy balance. GreenStart assisted three county conservation districts in applying for, and administering, NH State grants for wood ash spreaders, no-till grain drills, sub soilers and aerway soil aerators.

GreenStart's contributions to open source templates and knowledge sharing are facilitating expansion of county scale projects to state wide projects through enhanced communication and collaboration, illustrated through the change in behavior and increased collaboration by conservation districts. At the start of this study, there was a baseline of no significant collaboration, and by the end, there were numerous collaborative grant proposals, and shared programing templates, and boilerplates for insurance and equipment rental agreements. The focus on soil health and tools has resulted in increased energy and interest at the meetings and more engaged supervisors over the time period. The dialog and sophistication of the farmer interactions increased, as was observed through the nature of technical questions. Initial questions typically focused on definitions of soil health (what), while later questions shifted to cover crop mixes and equipment setup (how). The interest and application of the applied work and partnerships with NRCS, GreenStart and the Conservation Districts is reflected in a 10-fold increase in cover crop acres during the Soil Health Initiative from about 400 acres in cover crops to over 4000 (NRCS, 2014). GreenStart also observed expanded local network and logistics capacity, demonstrated through the greater number of conservation district-led workshops and events that required less technical support in each subsequent year by GreenStart.

Biodiesel is a trademark and charismatic product for GreenStart and a powerful symbol of "what is possible" through local examples, as suggested by Diderot's comments on Jethro Tull's work. Building and operating an open source biodiesel trailer provides GreenStart a backstop that makes many other conversations possible. Functioning local examples, like the biodiesel processor, shift the dialogue into *how* to do, rather than *if* something can be done.

Continued expansion of state wide equipment lending inventories now include multiple no-till drills, Aerways(soil aerators), wood ash spreaders, soil testing equipment, roller crimpers, sub-soilers, and yeoman's plows. All of these tools are a reflection of soil health understanding and are important to reducing energy inputs, building soil carbon, and improving water quality.

GreenStart's alternative approach based on the Physiocratic framework has also gained corporate credibility. In 2014, GreenStart was invited to present to the North East Sustainable Dairy Collaborative, and invited to advise in the creation of the Wolf's Neck research farm made possible by a 3-year, $1,693,000 grant from Stonyfield Farm and the Danone Ecosystem Fund.

GreenStart's work has also gained attention through leadership in the open source technology standards work groups of the North East Sustainable Agriculture Working Group (NESAWG), and Food Solutions New England, which are primarily funded by the John Merck Fund and Kendall Foundation. The successful approach to soil health outreach and open knowledge exchange also resulted GreenStart being invited to join the national Soil Renaissance Project funded by the Oklahoma-based based Noble Foundation and the Farm Foundation. GreenStart's work has also attracted international recognition from the London-based Virgin Earth Challenge (virginearth.com), which has assisted in validating, expanding, and contributing to the GreenStart network's technical capacity also expressed through the Farm Hack project (virgin.com/unite/business-innovation/farmers-geeks-hacking-agriculture).

Increased Adoption and Investment in Soil Health

There was a ten-fold increase in cover crops planted from 2011 to 2013. The result was over 4000 acres planted in 2013 reported by the NH Natural Resource Conservation Service (NRCS 2014). This increase in cover crops over a short period of time illustrates the potential of the soil health tools developed by GreenStart and the Cornell Soil Health laboratory, and the ability of these networked tools to increase both the messaging and the pace of farmer-to-farmer knowledge exchange. The potential for successful, participatory science exploration among a broader section of the population is also expressed in the general increase in open sourced manufacturing documentation that has expanded the GreenStart-supported Farm Hack open source website.

GreenStart continues to expand the on-farm documentation of new equipment such as combines, oilseed presses, drying equipment, dehulling, and cleaning equipment. In the summer of 2013, GreenStart imported and demonstrated grain and oilseed harvesting equipment imported from Asia that has dramatically reduced the cost and complexity of harvesting grains and oilseeds in New England conditions. It now forms the basis for engineering an appropriate New England scale grain and oil seed infrastructure. GreenStart successfully demonstrated the equipment at workshops around the state, harvesting canola, sunflower, barley, buckwheat, corn, beans, wheat, oats, and rye. The viability of the equipment has also engaged manufacturers and created opportunities to locally manufacture agricultural equipment. For example, the most recent purchase of a yeoman's plow by the Strafford County Conservation District was accompanied by contracts to fabricate the frame locally. Many projects underway include local manufacturing of equipment and components.

Feedback systems that helped identify barriers to greater participation

GreenStart held a special statewide session in February 2014, which drew stakeholders from across the state for feedback on current programing and to review the greatest gaps and leverage points to future work. Through this process, it was clear that the technical support of GreenStart helped early adopter farms demonstrate successful practices; the learning curve for the first farms integrating grains and oilseed into their production systems has been steep, however, and the next round of farms will have the benefit of knowledge gained by early adopters and their willingness to share knowledge.

Increased interest in on-farm grain and oilseed processing and production illustrates the importance of adopting adaptive and farmer-generated hardware documentation coupled with enterprise decision support tools. Success was measured in attendance at regional events by conservation districts and attendance at GreenStart conference presentations. This work is highlighted as a future area of focus for GreenStart. GreenStart's wider range of partnership farms has demonstrated a change in interest and acceptance for growing oil seeds and grains for feeds and on-farm processing. The observed change was in the form of reactions and dismissals in 2006-2008, to customer acceptance of the product at local markets in 2011-2014. An expression of this change is illustrated by commercial agricultural enterprises investing in activities that were pioneered by GreenStart. For example, The Full Sun Company (fullsuncompany.com) is building a commercial oil seed crushing plant, and recruiting growers to supply sunflower and canola.

Discussion

GreenStart serves as a social experiment in using an open and networked approach to create organization across a large network, but without creating a large organization. All of the activity described in the previous section was accomplished by providing a minimum platform, a vision, and standards for facilitating a conversation. GreenStart has been successful in affecting the regional agricultural conversation by bringing the networked and Physiocratic approach into policy and planning meetings, getting the approach adopted in print, and making measurable change in agricultural practices and attitudes across the State of New Hampshire (NRCS, 2014). GreenStart network serves as a statewide resource and network builder, and functions as a catalyst for action on the ground by linking farmers, designers, engineers, agencies, universities, and non-profit organizations.

GreenStart illustrates a contemporary application of the Physiocratic framework by engaging a diverse population in participatory research, soil health and agrarianism with the goal of changing behavior through direct experience and observations. Success of the approach was demonstrated by GreenStart's voice within conventional stakeholder forums and changes in farmer behavior. Challenges were observed in the network facilitation role that GreenStart plays due to the limited resilience of the organizational structure. The minimalist nature of network facilitation, and reliance on no full time staff or infrastructure, also make it challenging to measure and document contributions and impact in terms familiar to funding and academic institutions.

GreenStart has increased the size of the population that connects food and energy production systems and soil health, as measured by increased soil health practices, numbers of tests and the expansion of the Soil Health management planning process into a national program within NRCS. A similar pattern of interactions and awareness of soil health is emerging in partnerships with land conservation organizations that have expanded their mission to collaborate on the agricultural management of conservation lands.

Outcome and Conclusion

GreenStart has been able to change its activities from merely advocating what is theoretically possible, to illustrating with on-farm demonstrations. Participating farms are now involved in building community-scale agricultural infrastructure and soil health knowledge that increase food and fuel production while building soil and reducing energy needs. GreenStart's work promotes on-the-ground energy and farming practices, and supports changes in behavior that conserve energy, sequester carbon, and lead to more resilient communities.

GreenStart clearly identified the need for greater decision support and enterprise planning, and to facilitate the "lessons learned" from one farm to the next. GreenStart heard consistently that farms are willing to share their experiences so that others need not go through the same steep learning curves as they shift practices.

Other "lessons learned" from this case study include the following three points:

1. The open source manufacturing model is more about identifying relationships and a suite of products that demonstrate viability to justify manufacturer relationships and attention. GreenStart and the Cornell Soil Health Lab's survey of participants in the Soil Health Management Planning process also found varying levels of technical competence, which highlights the importance of building a support community with technical backgrounds.

2. The obstacles continue in the form of added financial, technical, social and biological complexity of adding on-farm capacity, and the inevitable resistance to change. However, there is opportunity to handle complexity through expanded documentation, collaborative tools, and a culture of trust that that creates incentives for exchange of knowledge as a benefit rather than a risk.
3. Building trust and legitimacy with the farmer participants is crucial to successful projects, highlighting the importance of farmer-validated decision support tools to help change the culture and to create relationships that spread knowledge.

Case Study Two – Farm Hack

Methods

Farm Hack was founded as an expansion of concepts incubated within GreenStart, and to test the social acceptance of open source culture in agriculture. The author co-founded the organization based on knowledge gained through the establishment of GreenStart. The structure for Farm Hack came out of work already started by GreenStart two years earlier. Observations for this case study were gathered first hand by the author as a co-founder and president of the board of directors. The internet traffic data was gathered using Google analytics. Due to the on-line nature of community and the database driven structure of the Farm Hack web site, the contributions and patterns of use of the community are all recorded, archived and publically accessible documentation as contributions by the community members.

Approach

The following section is an expansion of the GreenStart case study that tests the internet meme that "you don't need an organization to be organized." Rather than focusing on local in-person experiential learning and trust building, it instead focuses on the potential for open knowledge exchange beyond geographic boarders, and the creation of large and complex tasks developed through informal networks, collaboration, and volunteer efforts.

The Farm Hack case study is similar to the GreenStart approach in its network-based structure and operating platform that establishes rules, provides some collaborative tools, and orchestrates conversations to create an environment where content is almost entirely user-generated. The extension and scalability of the model is of particular interest to the Farm Hack case study, which also has the objective of turning users of tools into producers, and passive customers into active participants and designers of systems.

As discussed in Chapter 1, the conventional, centralized, deductive model of farm research, development and commercialization creates substantial social and environmental externalities. It has not produced the seeds, breeds, tools, and culture that can be shared or scaled for a resilient, regenerative, and just food system. However, one of the challenges in building sustainable agricultural systems is a vision for which direction to move. The diversity of stakeholders tends to introduce very different opinions on what constitutes desirable directions for development (Barbier 2012). Clearly, it is important to create collaborative problem solving tools that help build shared vision among stakeholders, thereby allowing for combining efforts and reducing duplication, while at the same time enabling independent development efforts.

While shared understanding is required to envision a common future, the development of collaborative networks to stimulate system innovation calls for methodical thinking and the development of tools that support that process. Farm Hack was created as an experiment in "learning by doing," in an effort to understand the system by trying to change it. Farm Hack is a case study used for merging contemporary communications technology with the Physiocratic social framework, which was established as a central purpose of the Farm Hack project during its foundational meetings. It serves as a test bed to observe the social, technical, and agricultural system reactions to the expansion and extension of the framework beyond geographic boundaries. It serves to generate systems feedback on an open source approach to research and development. This model challenges the social acceptance that the inventor/discoverer be the one who knows or determines the ultimate use of research or an invention, and instead tests the idea that the ultimate use will be collaborative and emergent.

Overview: An Online and In-person Agrarian Social Club for Knowledge Exchange

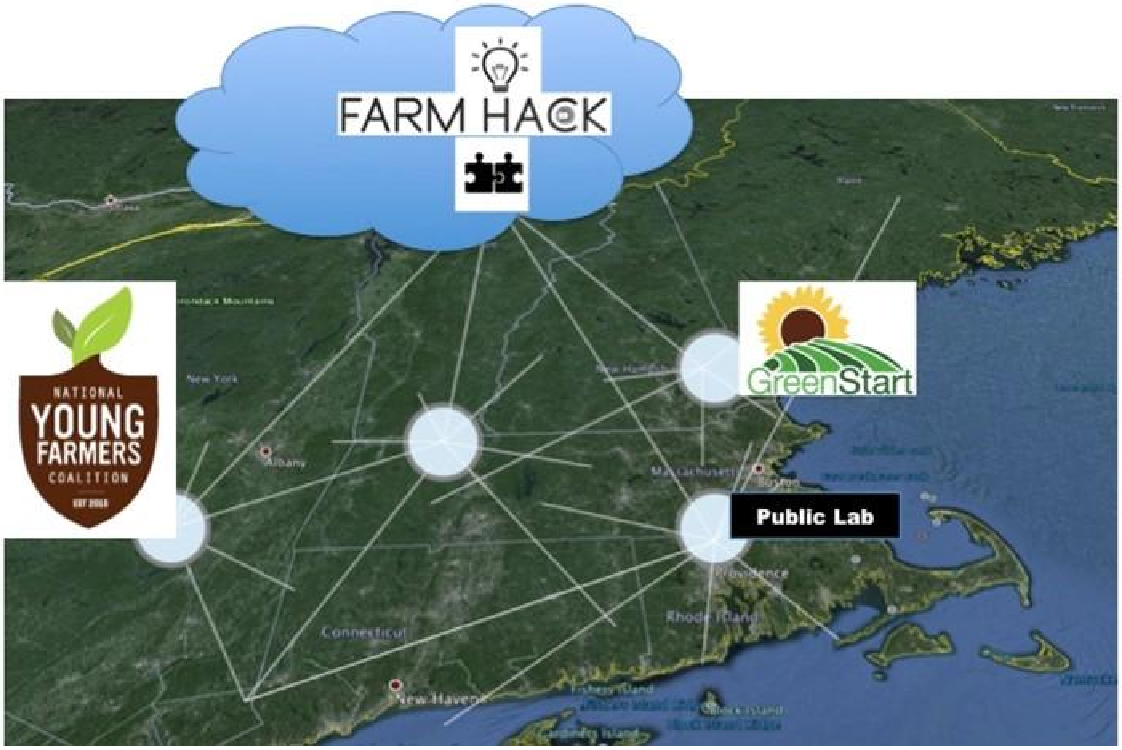


Figure 37 – Collaborative network based organizations. GreenStart and Farm Hack are experimental network based organizations that are testing the boundaries of creating organization without organizations. The role of the networked organization is to remove barriers to exchange and facilitate linkages by creating space for conversation and collaboration, and communicating a set of values. Both GreenStart and Farm Hack have come into existence as an exploration of these concepts and have been supported by more traditionally structured organizations.

In 2011, a community of farmers, designers, developers, engineers, architects, roboticists, and open source thinkers were invited by MIT to meet in Boston, Massachusetts. This first event was organized by the National Young Farmers Coalition, followed closely by many more events in partnership with GreenStart and the Greenhorns (a young farmer-artist collaborative). These events were promoted through organizational and personal social networks and drew on the desire of participants to make improvements in agri***culture*** that could be achieved by reducing barriers to knowledge exchange, and a belief that placing agricultural technology into the creative commons would reflect shared values and result in a more adaptive, open, and resilient food system. Farm Hack emerged from these shared

Enlightenment-based values that joined the seemingly disparate cultures of technologists and agrarians.

The Farm Hack community quickly evolved and expanded through on-line and in-person social networks, spreading across the east and west coasts of North America to become a global, user-driven, open source community of ideas. Today, Farm Hack includes thousands of active participants, with contributors from almost every continent, roughly in proportion to internet connectivity, and a growing repository of open source tools and skills documentation. It has demonstrated itself to be an effective networked culture of collaborative problem solving.

Both hacker and maker cultures are a natural, if not obvious, fit with the sustainable agricultural movement. Both cultures formed in response to ongoing hegemonic attempts to control access to resources (of technology and industry), and incorporated tactics that use open access to knowledge and sharing as a strategy to counter established interests that dominate industrial food and energy production. Hacking has been defined as a clever solution to a tricky problem by modifying something in an extraordinary way to make it more useful. As well, hacking means to reject the confines of consumer-defined culture, and to modify, improvise, and create new, customized forms (Anderson 2012). The use of this "hacking" definition comes from interviews and discussions within the Maker and Hacker movements including a panel discussion at the 2012 World Maker Faire in which the author participated. Innovation is an inherent part of agriculture, in general, and a critical part of sustainable agriculture, in particular. Identifying a problem, thinking of a solution, trying that solution, and assessing the efficacy while thinking of the next iteration is a daily practice on most farms.

In 2013, Farm Hack became a non-profit organization governed by representative contributors and organizations to oversee and facilitate the expansion of the network and contributions to the agricultural creative commons. Farm Hack maintains an active online community with thousands of volunteer contributors and provides a platform for collaborating across organizations and between individuals. The website hosted documentation for over 100 innovative tools within the first year, ranging from manufacturing instructions for newly created farm-built hardware such as garlic planters to "extinct" farm-scale tools documented for remanufacture such as oat hullers, greenhouse automation and sensor networks to organic egg enterprise business models, and open source software including the Farm Hack website itself. Many tools were modified with variations bouncing between the East and West coast and across to Europe and back again, with each stop documenting local adaptations. Since its founding, the Farm Hack prototype community has attracted over 500,000 unique users. If Farm Hack is able to expand to 1m users and 1% become contributors, it would create a research and development force of 10,000 that could be supported by a handful of people to maintain the software platform. A creative, passionate research and development team of that scale would approach that of large private corporations.

Despite being an all-volunteer organization, and operating without a budget or non-profit status until 2014, Farm Hack has partnered with dozens of organizations, universities, and open source and maker communities in the US and Europe which have hosted "live" Farm Hack events to document and improve tools, foster sharing, and build skills. Following the agrarian club tradition, these events have also involved lots of eating, drinking, and socializing. Public recognition has generated traffic and national foundation interest, as well as media discussion. Farm Hack serves as a case study for the applied framework proposed by this study. The framework proposed within this dissertation has been presented to the plenary sessions of the North East Sustainable Working Group, NOFAVT winter conference, the Quivira Coalition Conference in New Mexico and a Biodiversity, Water, Soil Carbon and Climate Conference hosted in Boston. The approach has also been recognized by the Virgin Global Earth Challenge, the Howard Buffet Conservation Innovation Prize, and the Soil Renaissance Project. It has been written about by popular press such as the NY Times, Wired, Make Magazine, Men's Journal, and PBS NOVA, and has been presented at many other conferences.

The Farm Hack events and web platform bring together farmers, builders, and designers and organizational partners including the National Center for Appropriate Technology, UCAL Davis, Draft Animal Power Network, Apitronics, GreenStart, Greenhorns, National Yong Farmers Coalition, Food Solutions New England, the Food Knowledge Ecosystem Project, Open Source Ecology, University of Vermont, University of New Hampshire, Groundswell Center, NOFA Vermont, NOFA New York, NOFA NH, Cornell University, Brown University, RSDI, MIT, Local Granges, SUNY, and The Intervale in Burlington Vermont. More partners are added on a regular basis.

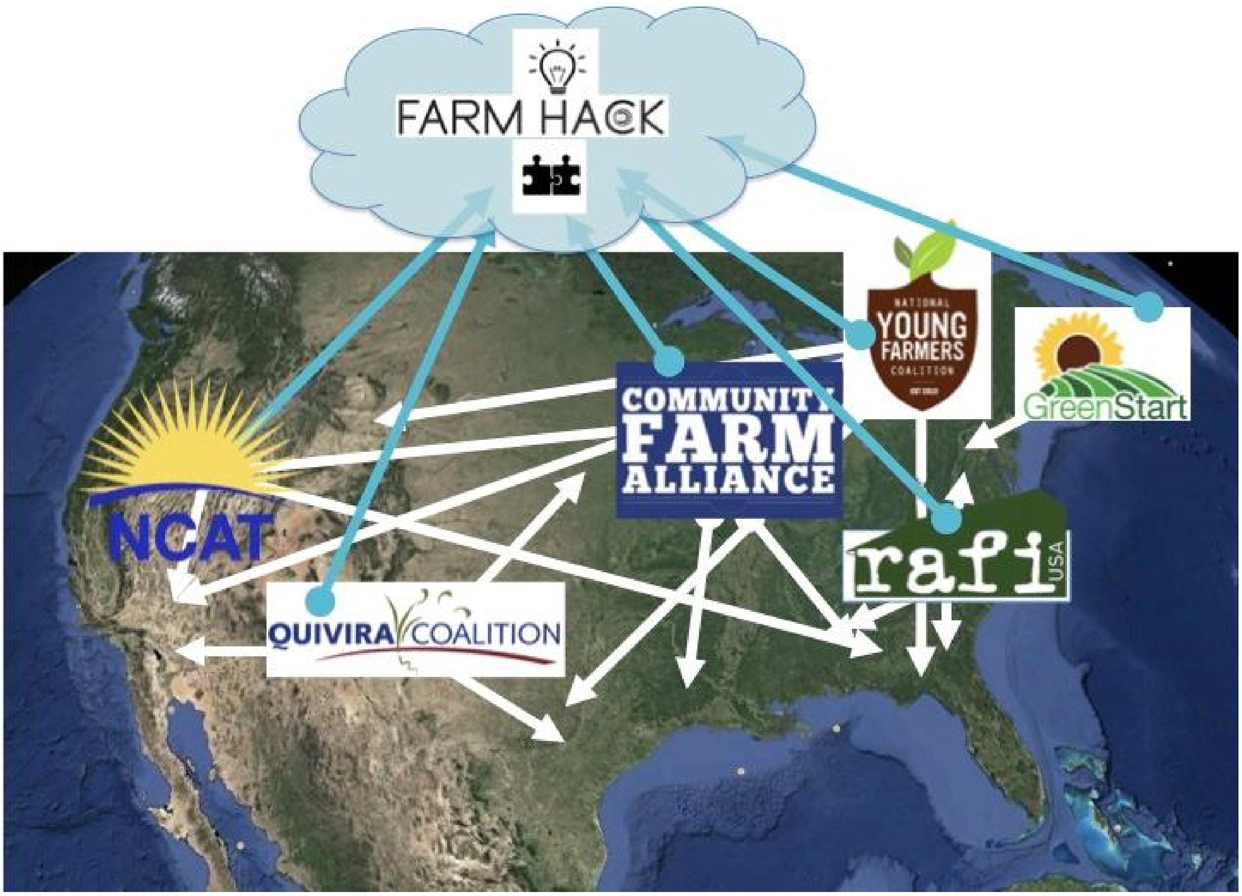


Figure 38 – Collaborative best practices create new learning communities. Organizational knowledge exchange and overlapping values converge through Farm Hack as a means to exchange knowledge and shared values across organizational boundaries.

The FarmHack.net site is also a tool and a collaborative expression of the community. It is the result of 710 hours of volunteer web developer effort and has had over 500,000 unique page views since 2012, with over 250,000 unique visitors resulting in 16,000 hours of user participation. There are over 2,000 registered contributors to the site, with 159 tools currently posted to the creative commons for adaptation and improvement. Further, there are 554 forum topics representing active engagement and discussion on issues relevant to sustainable agriculture, problem solving, and innovation.

Discussion

Farm Hack builds not only on the Enlightenment and open source software movement ideas that the natural state of knowledge is to be free, but on the Physiocratic world view of nature-governance (articulated by Quisney, Jefferson, Locke, and Franklin) that the productivity of the soil, and the education of the populace towards the ability to provide for their own livelihood, is necessary for the liberty and the health of a culture. In short, agricultural production is the root of sustainable civilization and therefore *not just an occupation, but foundational to* the shared cultural values of a healthy society.

Enlightenment thinkers pioneered the idea of crowd sourcing with the community-created *Encyclopédie: a Systematic Dictionary of Sciences, Arts and Crafts*, referenced in Chapter 2. The contemporary open source software community pioneered the development of networked tools, such as wikis, forums, and collaborative documents that facilitate collaboration and trust. Building on these models and their culture of voluntary reciprocity, Farm Hack confronts the assumed economics of agricultural research, and therefore challenges what questions are asked, what tools are produced, and how they are financed. The outcome is that *the tools, seeds, and techniques developed through this process both reflect and benefit those who intend to use them, not just those intent on selling them.* Farm Hack has built upon these pre-industrial and modern hacker/maker ideals of amateur inquiry by connecting farmers with other farmers, drawing upon a global library of skills and designs to create the potential for every farm to become a research farm and their neighbor a manufacturer.

By documenting, sharing, and improving farm tools and associated knowledge, Farm Hack is not just framing agriculture as a shared foundational economic activity but also illustrating an alternative template for local manufacturing. It is a model that provides greater choice and citizen control towards local self-determination. With this approach, the primary limiting factor in agriculture shifts from the (negative) extraction of scarce natural resources to the (positive) expansion of skills and systems understanding to harness the complex biogeochemical flows of atmospheric carbon, water, and nitrogen into productive and resilient agro-ecosystems. The emphasis shifts from efficient extraction to *skilled regeneration using all available knowledge*; our role as farmers becomes improving rather than diminishing the natural resource base.

In contrast, the conventional model for farm research, development, and commerce has illustrated a tendency towards biological “dead end” seeds and breeds, using closed technologies that create friction in each transaction and often cannot be shared, adapted, or reproduced. There is potentially more innovation happening on farms every day than in all universities and private labs combined. However, because of a scarcity mindset, very little on-farm innovation gets shared beyond the farm gate. Building trust across geography and promoting non-traditional community interactions is crucial to creating a culture of knowledge sharing. Farm Hack is built upon recognizing that farms are less competitive with one another than with global economic and climatic forces.

The documentation and communication required for open source research and development is not a skill set that is yet culturally established within agriculture. This is not a unique challenge, but is common to all open source communities. Fortunately, open source communities have the advantages of the cumulative accomplishments of and collaboration with other open source communities. Farm Hack's operating system has built on the strength of network structures and administrative tools developed by other open source communities, including Drupal, Wikipedia, Open Layers, and Apache, and has been able to build trust, grow, and adapt while making its own unique contributions back to the commons. In particular, it has been able to model the Collective Impact Framework as a backbone organization using collaborative tools to form common agendas, shared measurement, mutually reinforcing activities, and continuous communication across organizations and individuals to build trust as a new community (B. J. Kania and Kramer 2011). Mutually reinforcing activities also expand the value of the repository. The community benefits by identifying overlaps, building on the cumulative achievements of the broader open source community while reducing duplicated efforts.

Farm Hack's online platform is a prototype to reduce duplication of efforts and to find shared problems and creative solutions. Just as symbiosis is as powerful an influence as competition in nature, the same approach can turn the agricultural research and development system on its head by creating tools and cultural operating systems to reward, evaluate, test, share and build on the cumulative accomplishments of the community.

Outcome and Conclusion

By creating a voluntary community of support, and changing the economics of research, Farm Hack also aims to change the questions that are asked, and which problems get priority. The result is that the tools, seeds, and techniques developed are for the benefit of those who intend to use them, not just those who sell them: a demand-driven system rather than only supply-driven. It provides a response to particular types of market failures that fail to provide appropriate tools even in the presence of demand.

By documenting, sharing, and improving farm tools and associated knowledge, Farm Hack illustrates an approach to improving not just agriculture and local manufacturing, but also providing more choices and greater citizen control over quality of life and livelihood through improved social and technical tools. Agricultural history has primarily been a story of exploitation and extraction of both human and natural resources; however, there is a largely forgotten historical movement of great value in the natural philosophy of the Physiocratic thinkers. Farm Hack's vision for a more regenerative agriculture taps into both these earlier ideals and those of a new age of agrarianism that has emerged from Slow Food and other 21st century food justice and agrarian movements, merging their ideals with the shared values of the open source networked computing communities. Farm Hack expresses itself as an experiment to apply open source technology approaches to agricultural software and hardware and to the complex and knowledge-intensive bio-technical social system of agriculture.

Farm Hack's vision has built a working prototype for a more distributed economic system made possible by universal access to a constantly improving repository of ideas from the global community that can be drawn upon to adapt to local manufacturing and farming systems. The Farm Hack case study illustrates that the expansion of the creative commons is no longer a technical barrier, but is rather a matter of cultural persuasion as a counterbalancing force to hegemonic industrial forces. By creating open source repositories of knowledge, it is possible to bypass political power structures, shifting the balance from those who derive their power through the control of scarce resources and knowledge to those who derive it from innovation and creativity, mixing their skills with nature to create abundance based upon the most basic premise of agricultural promise observed by Jonathan Swift over 200 years ago.

Chapter 8: Adaptive Management, Open Source Research, and Social Media

Open Source Research and Development Theory and Practice

Adaptive management is a continuous inductive research and feedback process. Tools to gather systems-wide observations that can be used for management decision-making are both in effect and emerging. Realizing the full benefit of these efforts requires documentation, sharing, and feedback from a larger context. By expanding the context and leveraging individual efforts as open source validation, traditional professional researchers can provide greater return on observation efforts. A platform for adaptive management and data sharing serves as the same platform for collaborative research and development efforts to enable hardware to adapt and be shared across scales, to select varieties, to identify pathogens, etc. Adaptive management using an open source framework is not a particular solution, but rather a methodology for problem solving, management, and generalized knowledge exchange.

Social Network Overview and the New England Food Knowledge Ecosystem

The Farm Hack platform created the conditions for an open source adaptive management software system. The Farmier/FarmOS record keeping software tools emerged in parallel with Farm Hack and brings together social, technical, and biological feedback loops expressed in the user interface form of a management dashboard. Farm Hack focuses on shared problem solving to enable development, and takes the form of collaborative software. GreenStart also used collaborative tools such as shared documents and wikis to build a research network, and expanded tools such as Drupal, Open Layers and Etherpad to create the Farm Hack platform. The primary example, discussed in Part I, is the GreenStart facilitated Soil Health Management planning process created in partnership with the USDA/NRCS, NH Conservation Districts, the Cornell Soil Health Lab, and 18 cooperating farms and facilitated by GreenStart. The management project itself was coordinated using collaborative software in the form of Google Docs (collaboratively editable web-based-based documents) which created the foundation for interaction within the iFARM initiative to reach an even broader audience.

The New England Food Knowledge Ecosystem project (NEFKE) and Farm to Institution New England (FINE) also provide examples of network oriented organizations which have internalized systems-based approaches that embrace collaborative tools and processes. The methodologies articulated through their planning processes illustrate collaborative work across multiple overlapping networks. Both organizations are using the findings from the RE-Amp study, funded by the Garfield Fund, as a framework (Piestrak 2013). Those findings, which describe the characteristics of resilient and open source systems, are as follows:

- Start by understanding the system you are trying to change
- Involve both funders and non-profits as equals from the outset
- Design for a network, not an organization, and invest in collective infrastructure
- Cultivate leadership at many levels
- Create multiple opportunities to connect and communicate
- Remain adaptive and emergent, and committed to a long term vision (Piestrak 2013)

In each of these case studies, resilience is not just an implicit goal, but an explicit central organizing principle. In addition to resilience and open, knowledge-sharing networks, the related concept of Collective Impact (B. J. Kania and Kramer 2011) also plays a central role in the networked and collaborative planning dialogues taking place in food system network meetings across New England. The best practices identified within the Collective Impact framework have been officially or unofficially adopted by NESAWG, FINE, the Vermont Sustainable Jobs fund, and Food Solutions New England. They are:

The Five Conditions of Collective Impact Success (B. J. Kania and Kramer 2011):

1. ***Backbone Organization***: Creating and managing collective impact requires a separate organization(s) with staff and a specific set of skills to serve as the backbone for the entire initiative and coordinate participating organizations and agencies.
2. ***Common Agenda***: All participants have a shared vision for change including a common understanding of the problem and a joint approach to solving it through agreed upon actions.
3. ***Shared Measurement***: Collecting data and measuring results consistently across all participants ensures efforts remain aligned and participants hold each other accountable.
4. ***Mutually Reinforcing Activities***: Participant activities must be differentiated while still being coordinated through a mutually reinforcing plan of action.
5. ***Continuous Communication***: Consistent and open communication is needed across the many players to build trust, assure mutual objectives, and appreciate common motivation.

NEFKE articulates its first project element as the establishment of an information archive/hub that bridges the FINE/NEFKE/NESAWG networks. The design element of the hub is both about openness and reserves. NEFKE identifies the development of a new NESAWG.org site as an opportunity to build on open standards to enable complementary support to the new FINE site, and other food network organizations in the region. This includes data and information archiving/cataloging, data feeds such calendar and RSS feeds, and visualization tools. The process has already begun with a number of tools made publicly available through the network. An additional key element of the NEFKE project is the Linked Information Platforms which form easy-to-use, extensible shared resources.

Open collaboration is listed as a key assumption and part of strategic planning with FINE, LocalFoodSystems.org, Farm Hack and civic tools including Open Civic (gotopencivic.com) to support planned hackathons and collaborative development which will continually catalog and share new tools and applications. The approach taken by NEFKE is based on the extensive literature of participatory research and the requirements of adaptive management. These organizations and initiatives are creating examples of open exchange and collaboration within a dominant food system culture that is largely opaque and not adaptive to environmental or social changes.

New England Food Knowledge Ecosystem

Approach

The New England Food Knowledge Ecosystem emerged out of a working group of the North East Sustainable Agriculture Working Group or NESAWG. The working group sessions over a period of years identified the common need for shared knowledge and reducing the barriers to knowledge exchange across the landscape through shared standards, methodologies, and best practices. The case study presented here will focus on a particular aspect that had the most network overlaps in stakeholders, values, and technology with Farm Hack, GreenStart, and Food Solution New England efforts: the process of developing shared networking tool kits for collaborative networks using existing open source and collaborative tools. This approach, if successful, also creates new tools as a byproduct of an emerging regional food system network. In presentations to the NESAWG community, the development process was described by the author as the "blacksmith building the first tools."

Overview: A tool kit for collaborative networks

The New England Food Knowledge Ecosystem (NEFKE) was formed in cooperation with Cornell, the John Merck Fund and the North East Sustainable Agriculture Working Group, and incorporated the principle of openness into its operating principles. NEFKE and its work formally and informally overlap with the other case studies. NEFKE's website and planning documents state that, "Where possible, 'open' solutions and structures will be encouraged" (Piestrak 2013), including:

- Open source tools, systems and platforms

- Open access to existing knowledge resources and those generated through the ecosystem itself (e.g. case studies and user contributions)
- Open content that can be easily adapted or repurposed
- Open standards (e.g. UBL), technical protocols (e.g. HTTP), and specifications (e.g. RDF)
- Open science, making scientific research, data, and dissemination accessible to all

The organizational structure is based on the Collective Impact Theory covered in previous chapters, and exists within a subset of many other networked organizations. The project is organized as a working group within NESAWG, and the management team draws advisors from multiple stakeholder groups, including Farm Hack and GreenStart. The NESAWG role within the larger network has been to provide research and resources in the form of existing language and related case studies, to assist with the first stages of coordination while the organizations moved towards deeper collaboration. NEFKE, in its early stages, was able to provide a basic framework for conversation amongst organizations; it was also able, with support from organizations such as Farm Hack, to illustrate the potential for improved collaborative tools to support the social and technical processes of collaborative development.

Discussion

The Open Shops feature prototyped by Farm Hack was conceptually developed in a partnership between NEFKE and Farm Hack. The Open Shop concept allows individuals, organizations, merchants, and fabricators to feature their open-source designs and collaborative activity, and to create an entry "home" page to the Farm Hack content and tools. Open Shop is part of the experiment in trust-building and ownership within the community, allowing users to curate and showcase their own activity and interests to a particular audience while still contributing to the wider Farm Hack community. The Open Shops area is currently in a prototype version on the Farm Hack website, which itself is a Minimum Viable Product (MVP) or prototype. The development of Open Shops was identified as a strategic focus with detailed functionality developed and documented through numerous design build sessions called "hackathons." The collaborative functionality and "embedded" content model was prioritized in strategic planning sessions hosted by NEFKE in March of 2014 and illustrates the importance placed among the food systems groups in the Northeast in expanding collaboration and creating shared user-generated content.

Many organizations have open source projects, but Open Shops stands out as an expression of the meta-goal of providing an operating system for collaboration among organizational partners with shared values. As such, it assists with identifying overlapping problem statements, tools, and solutions. For example, Food Solutions New England and the Northeast Sustainable Agricultural Working Group dialogues include the development of a standards conference for open source communications across food systems. This project's proposed structure is facilitated by Farm Hack, and uses Farm Hack as the platform to develop the basis for the Food Knowledge Ecosystem Project administered by NESAWG. Most recently, the network has expanded to include collaborative dialogue with related international open source organizations such as the Open Food Foundation in Australia.

The Farm Hack Open Shops project illustrated in Figure 39 includes the following goals:

1. Improve the open shops collaborative on-line tool. Success will be measured in increased organizational and individual use and in the form of on-line feedback and tool ratings, and documentation downloads.

2. Increase the capacity within the farming and wider community to document, share and create their own open source projects by hosting instructional webinars and in-person events, and collaborating with organizational partners on an open source food system standards conference.

3. Improve the web-based interface to lower technical barriers for sharing open source projects. Success will be measured by a higher participation rate and fewer "lurkers."

4. Facilitate building, selling, and discovery of tools that reduce the economies of scale in agriculture by building a classifieds on-line tool. Success will be measured in the percentage of tools being sold, built, used, and documented by the community.

5. Document and expand Farm Hack in-person events that bring together people with diverse skill sets to create a more resilient food system with tighter linkages between customer and producer. Success will be measured by the diversity of community profiles and participation beyond farming membership.

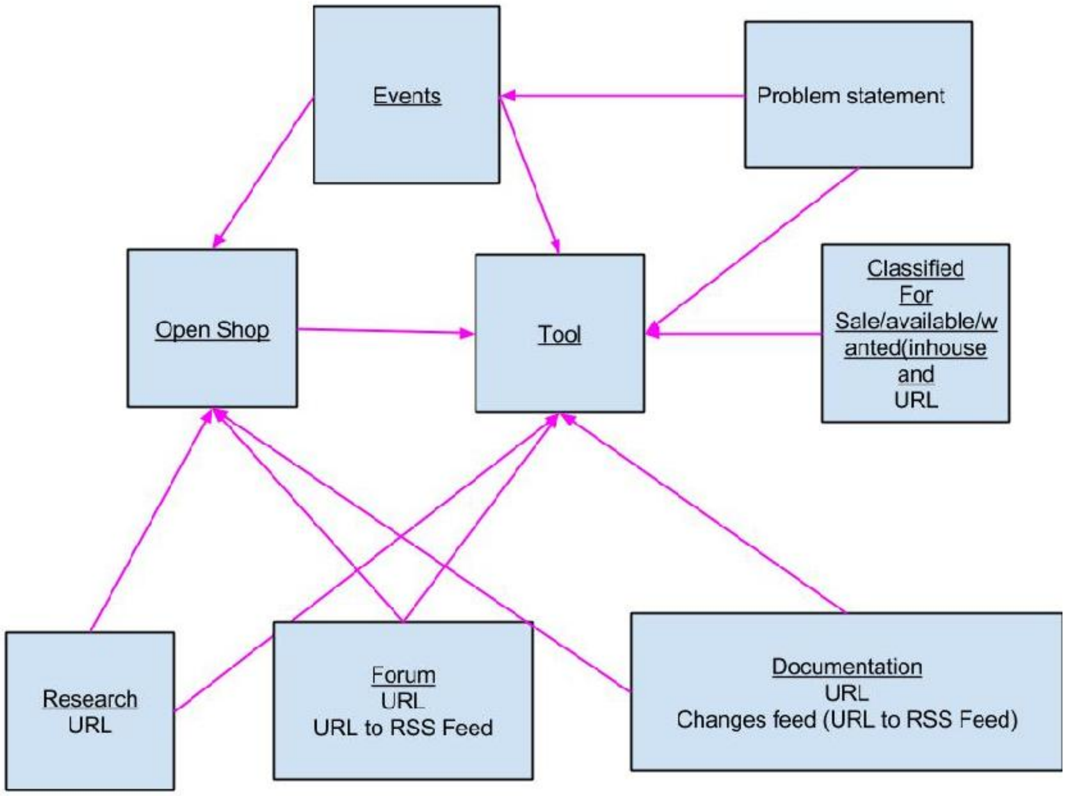


Figure 39 – Architecture of Open Shops Concept developed through NEFKE. The Open Shops concept aims to build collaborative best practices, and to reduce barriers to cross organization knowledge sharing. Each type of documentation represents a different aspect of knowledge exchange and a different part of the development and sharing process.

Other examples of shared templates and standards that have come through the overlap in stakeholder involvement include shared grant templates through the New Hampshire Association of Conservation Districts (NHACD), the opening and sharing of projects and infrastructure across New Hampshire county conservation district borders, as well as explicitly open source science and technology organizations such as Public Lab, DIY Drones (http://diydrones.com), Arduino (http://www.arduino.cc/), Mission planner (http://planner.ardupilot.com/), Flight Riot (flightriot.com), Ecosynth(http://ecosynth.org/) and Photosynq(http://photosynq.org/). All of these have contributed to and benefited by interaction directly or indirectly from the NEFKE project.

The NEFKE project holds a crucial role in the effectiveness and scalability of open source and collaborative efforts, as it recognizes that collaboratively generated shared standards are as important to improving incentives for knowledge exchange as collaborative tools and best management practices. The NEFK project provides another example of a network based approach and collective impact methods; this is illustrated by the expressed intention not to create a new organization, but instead to hold and champion the collaborative process and language while working with others to form "backbone" organizations that can carry the cultural practice of standards setting. Standards can play an important role in defining markets for sustainable innovations. However, Barbier (2012) warns that "they are usually enacted on the basis of 'proven' novelties rather than on what may be needed from a sustainability perspective. There is consequently a risk that standards become a barrier to further innovation, which makes it important for them to be flexible and 'progressive'"(Barbier and Elzen 2012).

There is, of course, great value in innovation beyond the level of sharing data standards. NEFKE, Farm Hack, and related projects have overlapping stakeholders and illustrate this by also adopting elements of collective impact theory and practice. In addition to statements of shared values, and continual communication, these projects embrace open source collaborative tools, such as Drupal, Open layers, Etherpad, and standardizing RSS feeds to enable content sharing and the inspiration of a wider learning community. This is possible because, contrary to widely held views, standards do not actually standardize practices but rather organize them so that the data can be exchanged more easily. In the case of NEFKE, this means enabling exchange of content regardless of where it is stored rather than centralizing data repositories. The challenge is to also implement standards that reward further innovation.

NEFKE provides an applied case of trust building in the network development process, illustrated by the tools identified in Figure (40).

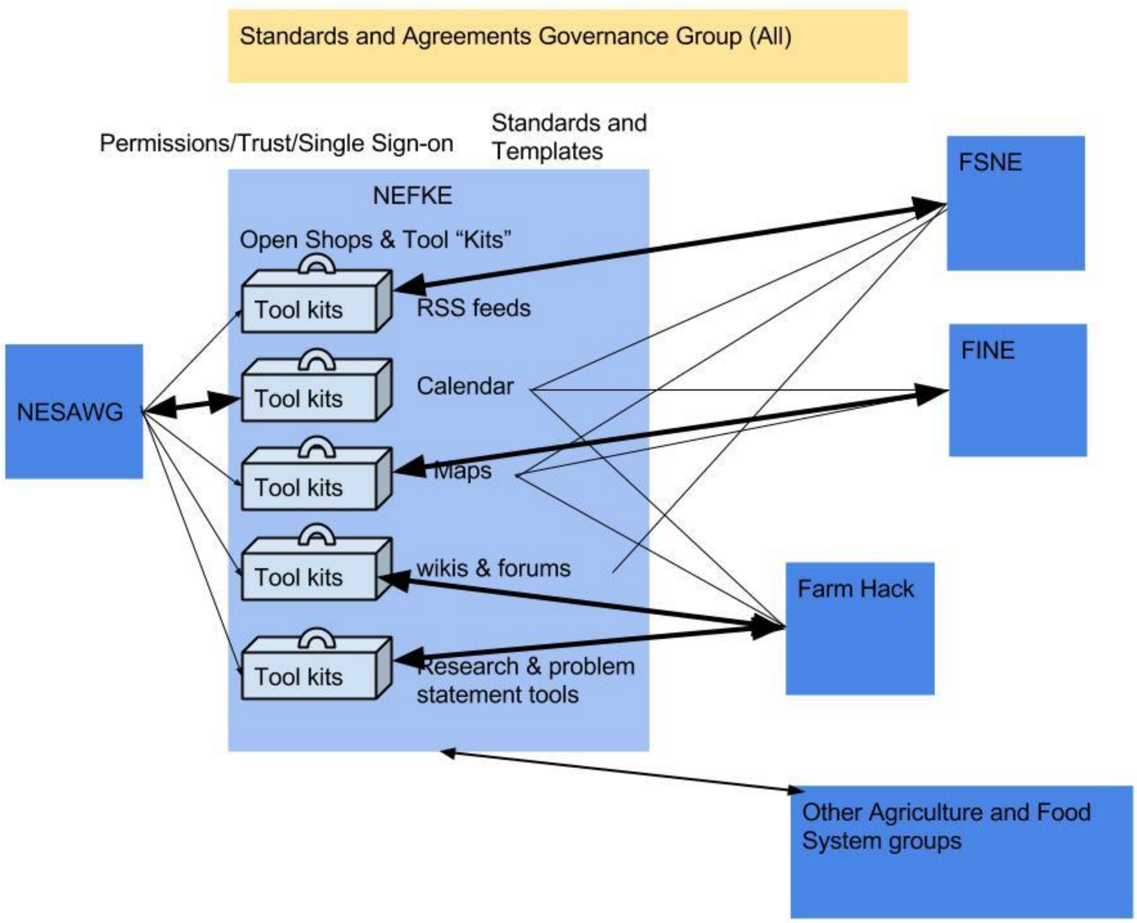


Figure 40 – Structure of shared collaborative tools created through NEFKE. The development of both the collaborative tools and the standards, also serves to build social bridges across organizations and build trust. The value of the collaborative tools also increases as the size of the network increases.

Barbier (2012) states that "the importance of trust building among stakeholders may seem trivial but in practice it is often overlooked in projects and change processes. If trust is lacking, actors may talk at length about issues of content but they will never find the common ground that allows them to move forward." NEFKE, the organizational structure, and references to collective impact literature all contributed to the building of trust that was critical in the initial stages of the process of introducing new tools and workflows between organizations. NEFKE's attention and endorsement of the Farm Hack project also provided legitimate standing within the broader academic and organizational structure that enabled an expansion of the community.

NEFKE has been successful in standards setting in the development of shared goals, RSS standards, Calendar framework, and other tools and language standards. However, the transformation of a socio-technical regime is a long-term process, and more complicated than the diffusion process described by classical, linear innovation models. In a transition, small parts of a regime start to change initially, as is indicated by the three-step process of true collaborative behavior. With further growth, new actors will become involved, which leads to further changes and adaptations, but to ownership and legitimacy of the process as the initial challenges of leadership diminish. The growth and transition to the expansion stage often require an additional step in a learning process (Barbier and Elzen 2012). A long-term process of gradual transformation also requires management as the novelty wears off and external support for the process diminishes.

> "The general view is still that government support should be given only in the initial stages until a novelty is 'proven', often only in a technical sense, and that thereafter it should be able to

> stand on its own feet. This, however, is not the way system innovation processes work. Longer-term policy support is required, although the type of support may change over time. As there is little experience in how to actually do this, it requires further investigation, often in a process of 'learning by doing'." (Barbier and Elzen, 2012)

This implies that management of transitions beyond the "innovative" phase and into the "implementation" phase is a long-term process that should be recognized and supported. Current policies do not tend to support this, but NEFKE and the collaborative process underway with Food Solutions New England, Farm Hack, and NESAWG can provide a longer term case study to revisit at future stages of maturity.

Chapter 9: Agrarian Social Network Tools - Case Based Studies

Social Expressions, outputs, and tools

The previous chapter identified placement of individual organizations and projects within the Physiocratic framework and used their "actions" to observe changes to system behavior. The study will now examine the output of the identified collaborative social systems in relationship to the generalized adaptive framework discussed in Chapter 3. This chapter will illustrate "flows" and feedbacks through the framework, and examine the products and evidence of Collaborative Adaptive Management (CAM) in action.

The Physiocratic theoretical framework provides social context and agrarian values to frame the significance of the open source research and development examples provided. The following case studies are presented within a historic context, but also identify new software and hardware tools that play a role in reinforcing networked activities and encouraging participation in agricultural science.

Soil Health Initiative and Management Planning Software

The Physiocrats believed that soil development was primary to economic development. This concept is useful when applying Mirabeau's Tree metaphor to reflect on the structure of contemporary agriculture, and in recognizing that the free flow of knowledge is still intricately linked to the management of the public good of regenerative natural systems. Knowledge exchange tools such as smartphones are now ubiquitous, but have yet to be directed towards soil health measurement. The adaptive management framework provides a method to measure complex heterogeneous indicators, yet to be developed, as an integrated system based on the generalized indicator, value, rating and systems health structure introduced in Chapter 3.

Limiting factors and the concept of constraints in agriculture are often used to understand nutrients. For example, soils testing is often concerned with measuring sufficient plant available nitrogen, potassium, or phosphorus, seeing if pH is in the right range, or if there is sufficient soil temperature and water. Systems knowledge is characterized by the complex interactions between individual constraints, the knowledge of which could also be considered a limiting factor. How knowledge is gained, how it is transferred, and what pathways develop from observation to management: all are significant to management decisions and outcomes. Social structures play a role in determining who has the power and resources to manage research and development, and how knowledge flows from field to management and back to the field. Open source systems, collaborative tools, and open ended reports like the Cornell soil health test work to remove social, hierarchical, and interdisciplinary barriers to knowledge exchange. Instead, their focus is on a conversation that begins with indicators, but that invites participation, recommendations, and collaborative problem solving to interpret those indicators.

The Social Aspect of the Cornell Soil Health Test

As discussed in Chapter 6, building trust and a sense of shared goals within a community is crucial for network-based organizations. In this regard, the Cornell Soil Health Lab approach to reporting and interacting with users is different and important. This differentiation is embodied within the layout of the Soil Health Report. In addition to providing a quantifiable measure for biological and physical health indicators in the "value" column of the report, the lab also provides a relative "rating" which is an easily identified color-coded traffic light, basically a "dash board" for the soil health report. This method not only serves as a decision management tool, but also provides social feedback relative to others in the system. In this way, network participants can give and get critical feedback not just about the absolute health of their soil, but also the relative health of their soil through rankings and ratings of practices within the database.

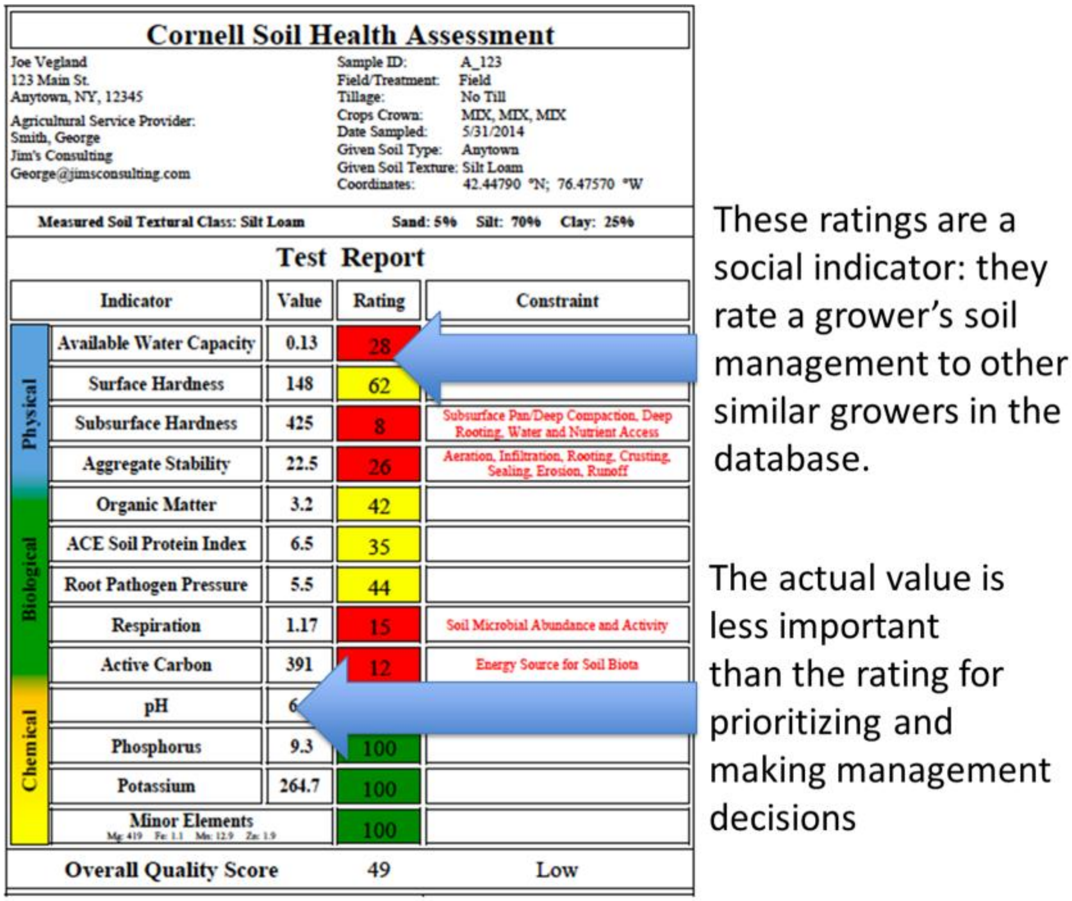


Figure 41 – Social structure of the Cornell Soil Health Test. The layout and presentation of the Cornell Soil Health Test illustrate a management focus to data. The data are presented not just as absolute values, but also relative to others within the data base. The relative rating carries with it social implications, and also opens the door to further analysis with other farms, providing insights that form the basis for the more generalized approach to participatory adaptive management.

The current form of the test relies on a simple comparative score within a given indicator based on all other similar samples in the database (Idowu et al. 2009). As more samples are added, the value of the ranking increases as well as the resolution. The soil health reports are currently distributed by email in pdf format; however, a mobile and web-based report is being developed in conjunction with GreenStart. The potential for the web-based version of the soil health report is to enhance the social feedback not just for soil health indicators, but for management decision support as well. Soil management decisions are specific to farms, but the decision making process and possible variables to consider from the physical, biological, and chemical processes are consistent across all farms. Rotations, cover crops, tillage methods, and amendment decisions can be facilitated by having access to what has worked (or not) for soils in similar condition within the database. The movement of the soil health management to a web-based application will facilitate the gathering of more detailed location data, and the addition of expanded sampling protocols such as soil image analysis, or more frequent or detailed indicators such as compaction, moisture, and pH. These can be rapidly field tested rather than lab researched, which opens the possibility for the "test" to be less isolated and more of an ongoing evaluation and decision making support tool. The same software capabilities that enable access to collaborative tools like Farm Hack can also be used to link farmers together for peer-to-peer decision support. Adaptive management becomes, in effect, a constantly evolving research and development process. A similar approach can be expanded to develop new indicators as electronically derived sensor data becomes available. Higher resolution and continual monitoring create the conditions for both social and economic feedback loops required for the universal adaptive management framework.

Building trust online has been a key to enabling transactions across the internet, and is a crucial factor in sharing environmental data. Social technology has developed in parallel with new measurement tools to address this issue in other fields, such as e-commerce, and are constantly improving. E-bay developed vendor and buyer ratings in order to provide a measure of trust between anonymous parties conducting business; companies like couchsurf.com and Airbnb, that are pioneering the sharing economy, are viable because of trust in reputation ratings. Active on-line forums and wiki editors develop histories and peer ratings that carry weight within the community (Richters and Peixoto 2011; Buskens 2002; Sherchan, Nepal, and Paris 2013). The sharing of soil, environmental, and agricultural practices data will require similar systems and methods to build trust and provide sufficient benefits to participants. As sensors and data loggers continue to drop in cost and increase in accuracy, a networked platform will improve the database of stored values. Associated decision support improves with producer feedback, which in turn will increase incentives for participation.

This horizontal method of communication and the mutual trust required for the system to function also has the potential to ***reduce the social gap between agricultural scientists and farmers***, which has been identified as one of the primary challenges for participatory and on-farm research projects (Riley and Alexander 1997).

The pace of peer review, and access to data and publishing, will also be affected as large data sets become available through agreements with producers. The quantity of data generated will, in essence, make data sets less valuable, but instead emphasize the quality, frequency, and community relevance of the analysis. Environmental models can be validated more rapidly by having access to more data points to refine regression analysis, and in the process also become more transparent to users. Modeling tools become valuable as planning tools as they become integrated into the decision support process.

Additionally, mobile web-based data collection will enable the soil health management planning process to plug into other management software. A structure for open source adaptive management software is proposed in Chapter 10.

Innovation in open science and community development

iFARM (Imaging for Agricultural Research and Management)

Method

As discussed in Chapters 1 and 3, participatory research has the potential to be both cutting edge and high quality. iFARM events build on the combined efforts of Public Lab, GreenStart, and Farm Hack communities already discussed in this chapter, with the stated intention of creating better observation tools, shared data, and an engaged citizenry through an active learning community. The iFARM initiative offers a counterpoint to conventional closed-source scientific research hardware and software, and operates as a system of participatory amateur inquiry. The participants at iFARM events are motivated by the belief that without open source research methods, many tools and techniques, even with radically reduced prices, will remain in the exclusive realm of consultants or hidden behind pay-walls. iFARM was created as an interaction of the case-based studies already presented. It also serves as a case study for the cumulative effect of this learning community, reflected in the rapid increase in sophistication and expansion of technical skills and scope from year to year.

Results/outcome

The first iFARM event in 2012 was held on a single day and converged around the imaging of no-till cover crop plots discussed in Part III, Chapter 11. Weather balloons and kites were used as aerial platforms utilizing very basic canon hacker development kit (CHDK) scripts running on the cameras. Post image processing included early paired image NDVI scripts and hyper3D structure from motion processing using Meshlab. The images were georeferenced using mapknitter, an open source tool developed by Public Lab based on open layers tools. The resulting geotiffs were later accepted into the public Google earth map layer.

The second iFARM event in 2013 expanded from a single day event into a two-day social hackathon. It focused on smart phone and web cam based spectral data equipment that was just mature enough to test as well as early near infrared infragram camera prototypes. The focus was on ground truthing and calibration using commercially available scientific equipment. The primary aerial platforms remained kites and balloons, but the event added a 40' pole camera with a remotely controlled gimbal that tested live camera video feeds. Some members of the community demonstrated the early stages of multi-rotor and fixed wing aircraft mapping platforms, but they were not yet mature enough for full missions.

The third iFARM event in 2014 broadened in scope and participation into three days of programing. The first day focused entirely on UAV field setup operation with four universities being represented. Thousands of images were collected with several UAVs flying autonomous missions using sophisticated camera scripts that interacted with the autopilots. The second day focused on technical presentations to share the past year's accomplishments. The presentations included Infragram, Spectra Workbench, FIDO, Apitronics, Cow Tracker, the Growing Clean Water Initiative, an open penetrometer design, soil imaging and the beginning of image calibration approaches. The emerging structure and relationships of the hardware, software, and management feedback are captured in the indicator, value, rating and health framework for adaptive management and research and development proposed by this study.

Open Source Hardware is Software - Farm Hack and Open Source Knowledge Exchange

The open exchange of agricultural knowledge and tool designs was underway long before the invention of the internet, as illustrated by the historical review in Chapter 2. The new development in open exchange is the contemporary communication technology now available to remove barriers to the flow of ideas.

The growth of the open source movement has been partly the extension of the software development culture and methodology into organizational structure, business models, and hardware. Open source hardware is, at its essence, the communication of "genetic code": the blue prints, associated documentation, and assembly instructions to replicate and build new hardware. In that sense, it is simply an extension of software, and can even quite literally be communicated in the form of software code as machine language instructions for precision manufacturing equipment such as 3D printers, lathes, CNC machines, or pick-and-place circuit board printers. In some cases, it can be documented and communicated in a form as simple as a photograph or line drawing. Hardware is simply tools that reflect our understanding of the environment and how to manipulate it; the description of hardware and its context is also documentation that can be digitized, modified and shared. Knowing this context is crucial for understanding the case studies that follow and for understanding the successful hardware development projects that the Farm Hack, Public Lab, Adafruit, Arduino, 3D-Robotics and Apitronics communities have built. The following tool examples illustrate representative innovation types and knowledge exchange processes that developed as patterns of use from user generated content on the Farm Hack platform.

Adaptability to Changing Technology and Farmer Needs

FIDO was one of the first projects developed within the Farm Hack community through the farmer-driven design charrette procedure. The project captures the convergence of open source culture, agriculture, and newly reduced costs of electronic circuitry. The FIDO concept developed out of a grower's problem statement that identified crop losses in greenhouses because the feedback process of manually checking remote locations resulted in air temperatures that were too high or too low. The first prototype solution created a basic system that would text message the farmer (or anyone else) if the temperature was out of range. The FIDO project fits within the adaptive indicator structure outlined in Chapter 4, and was quickly adapted to provide an automatic data feed and text message alerts for other farmer-defined indicators. The FIDO project illustrates the successful convergence of hardware, software, and open source culture in creating adaptive management tools.

The open architecture of the FIDO project also enables integration and adaptation as new technology becomes available. The first FIDO projects were released on cellular networks; the second generation data loggers made by Apitronics were based on Xbee 915Mhz wireless radio protocols. But, during that time, the cost of increasing the range of Wi-Fi on farms also dropped dramatically when Ubiquity, a wireless hardware manufacturer, introduced low cost Wi-Fi bridges that enable Ethernet speeds at distances of over a mile. The US State Department funded an open source mesh network project called Commotion Wireless that enabled these bridges to run software to make them into Wi-Fi hotspots. This software greatly reduces the cost and complexity of connecting and makes whole farm Wi-Fi possible for a few hundred dollars; affordable and accessible software shifts the hardware options for problem solving to higher frequency environmental monitoring and alerts.

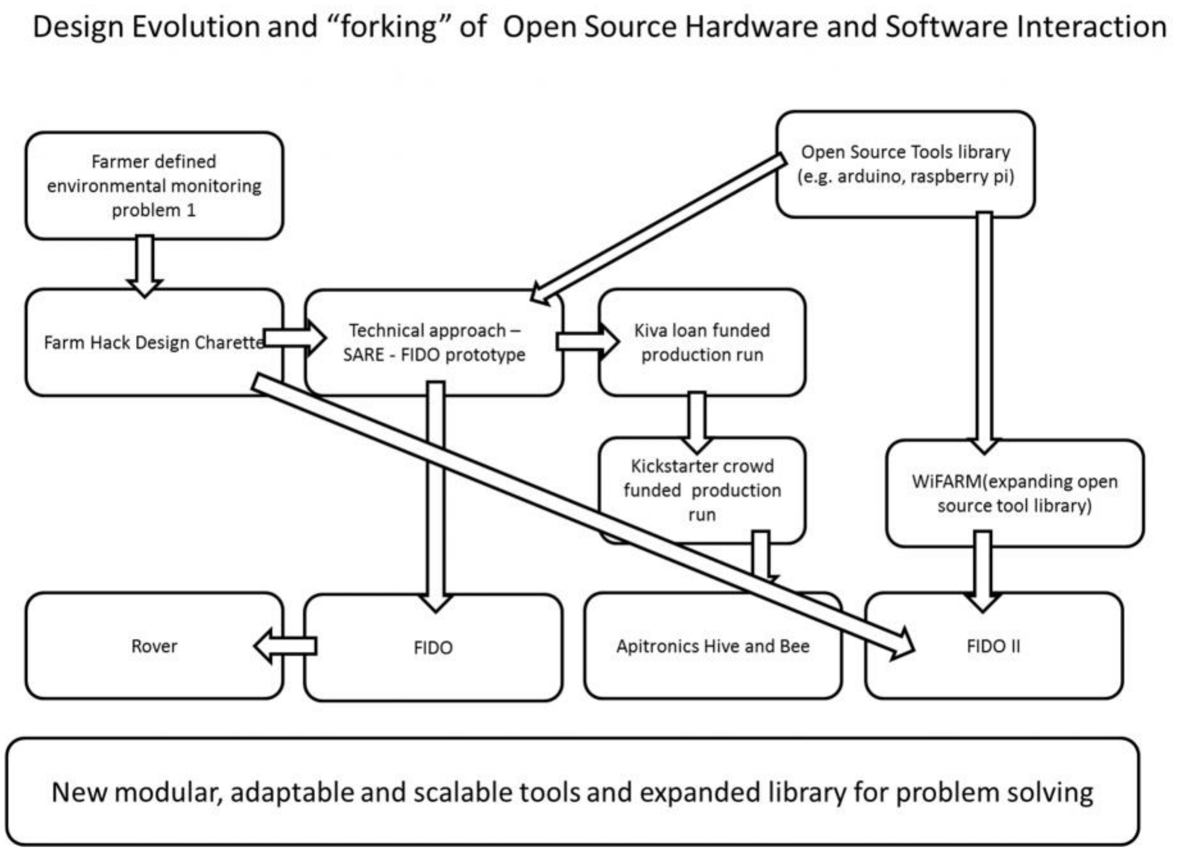


Figure 42 – Evolution of technology through knowledge exchange and collaborative process. Technological branches are facilitated by publishing accumulated innovations. For example, the Rover electric fence controller was a branch of the FIDO project development. The FIDO II project bypassed development steps by building on the original concept, but with newer open source hardware platforms.

The adaptation and flexibility of tools and their ability to be combined easily illustrates the open source socio-technical interaction. The FIDO project was quickly copied for other data logging and monitoring jobs such as climate control, electric fence, and water monitoring. The full history, design logs, and conversations related to the development of FIDO are archived, and are publicly accessible on the Farm Hack website ("Farm Hack - Fido-Temperature-Alarm-Sends-Text-Messages" 2014).

Designs Revived From Extinction Through Documentation

The Farm Hack platform also supports the re-manufacturing of products that are no longer manufactured but were once commercially available. The impact oat huller tool posted to Farm Hack represents a prototype built from archived engineering drawings shared and demonstrated at a Farm Hack event. The engineering notes were digitized, posted as a tool wiki on Farm Hack. The drawings were digitized and modeled in Trimble Sketchup and posted the 3D warehouse library of models for public sharing. The freely downloadable Sketchup file enables the design to be translated into a CAD file for fabricators. Design improvements and modernization of the design were also suggested through forum conversations that extended the functionality of the design to function for other crops such as spelt and barley ("Farm Hack - Oat-Dehuller-Model-Sr-50" 2014).

International Adaptation of Technology (from Europe to USA)

The Farm Hack platform also functioned to transfer designs between countries and adapt the designs to local conditions and available materials. For example, the Triangle Hitch tool is used to improve the three-point hitch implement attachment system, and makes switching implements faster and safer. Commercial units were either unavailable or available at a cost substantially above the cost of materials. An alternative design was developed and published to the creative commons in France by a Farm Hack partner organization called ADABio. Through a Farm Hack tool post and a subsequent event, three adaptation methods were developed based on the French plans to translate the design from metric to standard steel stock available in non-metric countries. The contributions to the project flowed from France to New England, with refinements contributed by farmers in Quebec. New design and latching mechanisms were developed, documented, tested, and shared ("Farm Hack - Triangle Quick Attach 3 Point Hitch" 2014).

Hardware Design Modification from USA to Europe and Back

Hardware designs were also transferred from the United States to Europe and back again, illustrating low barriers to knowledge exchange. The roller crimper, a tool that mechanically kills winter annual crops by crimping the stems, was developed by the Rodale Institute as part of their organic no-till research initiative. In 2010, the Rodale Institute made their tool design open source. The open source design was manufactured locally in Pennsylvania. GreenStart purchased two for local trials in New Hampshire, and the design was posted to Farm Hack. Other designs, modifications, and adaptations were subsequently added to the Farm Hack tool wiki page. The new postings came from Pennsylvania, New Hampshire, France, Quebec, New York and Germany. Each post adapted and improved function based on particular local conditions and needs, with improvements to the design from France being actively adopted in New Hampshire and New York within a year ("Farm Hack - Cover Crop Roller" 2014).

Adaptation and Scale Reduction of Industrial Technology

Farm Hack also illustrates knowledge exchange across industry scales. Biodiesel knowledge exchange and open source designs pre-date the creation of Farm Hack, with many early designs posted to forums such as biodiesel.info.pop, and biodieselnow.com. In 2008, these web sites and communities also promoted California "maker spaces" and "skills" fab days/workshops that brought together passionate amateur fuel makers to build and improve biodiesel processers, an early example of industrial knowledge being exchanged and adapted for and by an amateur open source community. The development of the first mobile biodiesel processing plant was inspired by the "appleseed" workshops in 2008. The design was then improved upon by Piedmont Biodiesel in North Carolina, before GreenStart created the fourth generation prototype. The biodiesel trailer was GreenStart's first open source project; it inspired the creation of the Farm Hack web site to improve upon open source documentation tools, and led to the documentation and implementation of basic open source design principles. Farm Hack built upon design elements from the early biodiesel forums. The biodiesel trailer represents a project that would not exist except for open source research methods, tools and techniques, and on-line forums and wikis. The biodiesel trailer also represents one of the more complex tools that will serve as a test case for improving technical documentation of design, manufacture and use of tools ("Farm Hack Tool - Mobile Biodiesel Processor" 2014).

Part III – A Technical Review: Agricultural Adaptive Management Feedback Systems

Chapter 10: Technical Framework and Adaptive Management

Part I and Chapters 1-5 outlined a Physiocratic framework and a theoretical foundation for approaching adaptive management. Part II and Chapters 6-9 explored the social and economic applications of that framework. Part III focuses on the technical process of measuring environmental indicators that feed into an adaptive management system built on the Physiocratic framework. Two case studies are used to illustrate the workflows and methods in the context of currently available and accessible technical tools. Chapter 11 explores the workflow of remote sensed imagery analysis of agricultural research plots taken from consumer grade equipment for accurate species differentiation. Chapter 12 explores the workflow of volumetric calculations from three dimensional point clouds generated by similar consumer grade cameras for use as an indication of plot biomass and crop yield calculations. Both chapters discuss the results in the context of generating "popular" agronomy by exploring the ease of sharing and analyzing data and images within a larger agricultural and social context as described in the first nine chapters.

The Physiocratic and adaptive management framework, as described in the previous chapters, depends upon incremental social and technical achievement, embodied by open source technology. An exhaustive review of tools is not feasible because of the limited scope of this study, the dynamic nature and rapid rate of change, and the independent nature of the supporting communities. However, this study has chosen representative tools and field studies to “prod” the system and generate observations of the socio-techno-agricultural interactions illustrated by open source citizen science monitoring of agricultural field trials.

The achievement of a ‘post-industrial’ society will not necessarily result in a more sustainable society that is characterized by a better balance between economic, social and ecological goals (Barbier and Elzen 2012). Without social transformation, as articulated through the Physiocratic Framework and modeled by adaptive management, negative externalities will likely continue; greater technical advancement of observational technology will not result in more resilient agricultural systems without a coinciding cultural shift. A primary goal as articulated earlier in this study is to expand participation in natural resource management by increasing observational accuracy at lower costs to enable adaptive management. The purpose of Part III is to examine the state of technology with regard to these goals and document the current challenges and limitations. The same "learning by doing" and “prodding the system” process is used in this analysis, including field experiments to create and test sample methods and software work flows. The work flows are not the only possible approaches, but represent one iteration of each type.

Because of the focus on cost, accessibility, participation, and accuracy, the technical examples and experiments in this section are not testing a biological hypothesis so much as acting as indicators themselves of the maturity, accessibility, accuracy, and usability of the systems they represent. From this perspective, the camera is not as important as a scientific instrument as it is an indicator of the technical potential and the social system that modified it, and the social context into which it is being released as a tool.

Similarly, the field trials and experiments are presented as indicators of the accessibility of the system, and the challenges in applying this technology in a real world situation. This approach provides an indication of the technical system path towards or away from the desired state of low cost, highly accurate, highly accessible research with broad participation.

Technological Context: Remote Sensing and Adaptive Management

Adaptive management is dependent on receiving rapid feedback from managed environmental systems (Holling, 1978) and (Walker, B., & Salt, D. 2006). A framework and workflow from participatory open source methodologies is emerging to calibrate image analysis methods that can distinguish species composition and abundance, as well as other environmental conditions in agricultural plots using multi-spectral imagery. These processes provide promising data collection methods that are faster, less labor intensive, and lower-cost than destructive biomass sample analysis. The emerging “Internet of Things” landscape is made up of blends of hardware, software, and overlapping networks of open source communities. The collaborative development model of shared risk and reward changes the culture and economics of asking questions, and increases paths for participation and expanding the knowledge sharing community. As previously discussed, because they are both knowledge driven, open source communities are well matched to the principles of adaptive management. Because of these similarities, they share many of the same community development tools and methodologies.

Chapter 4 covered the newly available high resolution consumer-grade digital cameras, open source camera firmware programs, computer vision software, and low cost hobbyist remote controlled aircraft, kites, and weather balloons that enable the generation of large volumes of high resolution images. Organizations such as Public Lab, discussed in the previous socio-technical analysis, have also developed low cost multispectral adaptations for digital cameras. New low cost tools enable an exploration beyond Normalized Differential Vegetation Index (NDVI) to Differential Vegetation Index (DVI) and the development of customizable indices to target a particular spectrum. This is made possible by the greater resolution achieved by using imagery below cloud cover and the low marginal cost of filters and computer aided post-processing capacity. Chapters 11 and 12 apply these tools and workflows to illustrate how they intersect with "ground truth" data collected with traditional agricultural plot analysis techniques.

The transformation in agriculture and adaptive management has the potential to follow patterns of development in other disciplines that have already taken advantage of greatly improved imaging and observational tools and digital communications technology. The medical field, in both research and practice, has been revolutionized by imaging and communication of 3D images, and provides an example of implementing sophisticated inductive methods to assess systems health in the human body. The fMRI, CT scans, x-rays, EKG monitors, ultrasound, and other tools, provide equivalent cases and logical analytical processes that require a similar infrastructure to communicate as in agriculture. The toolbox for landscape-based analysis includes imaging and telemetry based sensors that can include ground based wireless network and data logging color calibration methods and markers as ground control points. Tools such as genome sequencing, not only of the human genome, but also of symbiotic human bacterial populations, have profound parallels to the open exchange of knowledge and shift in approach to systems based analysis in environmental science; these parallels can help form links between adaptive approaches to human health and environmental health.

Just as medical systems require the integration of data streams to develop a picture of human system health, the Physiocratic framework and adaptive management process forms the basis for software architecture to integrate disparate observations to assess systems health. The adaptive management layer is an interpretive user interface that creates a "view" based on available APIs that enable data to be pulled from across a landscape and from a variety of sources to create custom decision support processes. This data architecture enables constant evaluation of indicators and becomes a method for social interaction and communication of indicators and whole systems evaluation. The Cornell Soil Health structure, presented in Chapter 3, provides a foundation for this method by introducing the core concepts of Indicator, Value, and Rating structure which, when aggregated and viewed in context, provide general and adaptive measures of systems health.

The remaining portions of the technical evaluation will be dedicated to describing data flows from imaging within this context.

Historic Context: Aerial Imaging and Computational Power

Imagery is a method of capturing large quantities of data that can be interpreted using inductive methods by identifying observable patterns. Changing the position of observation is a critical element of reducing observational bias that is inherent in inductive methods.

Putting cameras on flying objects pre-dates the invention of the airplane and was one of the first uses of photography once the equipment became small enough to hoist in a balloon; the first aerial images were captured in 1858 (“History of Aerial Photography -Dark Room in a Hot-Air Balloon” 2014). The development of high resolution consumer grade cameras combined with other advances in lithium polymer batteries, memory, brushless motors, and computer processors has made low cost UAV (unmanned aerial vehicles) and UAS (unmanned aerial systems) possible as aerial platforms for agricultural remote sensing. The images contained within this dissertation’s analysis are significant in what they communicate, but are most significant for the open source and low cost processes that made their creation possible. The images generated within this dissertation were created with equipment and software costing less than $600, and could be generated for significantly less as costs continue to drop and techniques are refined. The total system cost for this equipment represents well less than 1/10th of low-end commercially available systems of similar technical specifications, and 1/100th of others. For example, Trimble, a well-known GPS and farm automation company that recently acquired both Sketchup and Soil Information Systems, announced that in 2014 it would offer an agricultural flying wing

UAS for $50,999 (Floyd 2014). The bill of materials cost of the components and sub-components in such a system is negligible, and illustrates the price extraction premium added by corporate overhead. It also illustrates how open source systems introduce a transparency in pricing of hardware components and accelerate innovation and accountability in research and development within the marketplace.

In 1525, Albrecht Durer rendered a series of now-famous images in a treatise on measurement. These images all illustrated draftsmen in the process of using drawing grids to render various three-dimensional (3D) objects in perspective. His approach changed the relationship between material objects and representation with profound effects. The capacity to represent accurate and mathematically defined objects and spaces was revolutionary and resulted in empirical science that has given rise to modern engineering and manufacturing. More recently, a similar argument has been made that draws a line from Da Vinci to modern CAD (computer aided design) that underpins the techniques (Gurevitch 2014) explored throughout the technical case studies provided in this dissertation.

Manually collecting and documenting vegetation and environmental conditions is time consuming, expensive, and tedious, which reduces the potential participants, especially amateur and voluntary participants. Despite these limitations, manual data collection of soils, vegetation, and water is the standard and validated method for collecting agricultural field data when a plot combine or plot forage harvester is not an option. Advances in precision agriculture have yet to appear in smaller scale equipment or less automated harvest and planting equipment, and have thus not yet lowered the cost of participation or expanded research activities. The industrial commodity application of precision agriculture relies on expensive proprietary systems integration. As low cost open source remote sensing and data analysis tools become more accessible and automated, the potential for creating APIs and related applied research methods to inform management practices increases. The potential exists for these data systems to run on distributed platforms to match or exceed the accuracy of the industrial closed and proprietary systems. Ground-based sensor networks will also be mentioned as a ground truthing method; t he data outputs from sensor networks is already in a quantifiable data log, which makes exchange and calibration comparatively simple in comparison to the technical challenges of image analysis. Imaging produces rich data sets, but requires extensive processing to produce quantifiable digital data streams and requires libraries for calibration and pattern interpretation.

Despite the added post-processing requirements, there are great advantages to aerial image analysis. As discussed in Chapter 4, digital image sensors are now very inexpensive and are not consumable or biofoulable, such as contact-type sensors which may require cleaning or frequent replacement of disposable parts. Imaging is also a non-destructive and non-invasive method, and produces rich data sets that can be gathered at high frequency if weather permits. Platforms for imaging are covered in Chapter 9. Light conditions and image calibration, large file size, and computationally intensive data processing requirements to generate quantitative data from images, although disadvantages, are increasingly being addressed by lower cost digital hardware and open source software also covered in Chapter 9. Imaging requires a less complex technical networking infrastructure in the field to operate. The disadvantage is generally a higher set-up cost due to the physical nature and complexity of field deployments of large numbers of networked devices. However, just as with traditional data collection methods, these techniques are most powerful when used to complement and calibrate one another.

Open Source Technical Support

Open source technical communities provide a viable substitute for corporate overhead and speculative or venture driven research and development. The technical community landscape that generated and supported the workflows outlined within this section are represented in the following table. These communities are an extension of the open source network covered in Part III Chapters 11-12.

Key Open Source Software communities		Public Education & Social Network Communities	Biogeochemical Environmental Models
Open Layers openlayers.org	**DIYDrones** (diydrones.org)	**Conservation Drones** (conservationdrones.org)	**DNDC** (UNH) (dndc.sr.unh.edu)
FarmOS (drupal.org/project/farm)	**Meshlab** (meshlab.sourceforge.net/)	**Flight Riot** flightriot.com	**Adapt N** (Cornell) (adapt-n.com)
ImageJ (imagej.nih.gov/ij/)	**QGIS** (QGIS.org)	**Public lab** (publiclab.org)	**USDA Nutrient and Manure models** (ars.usda.gov/Main/docs.htm?docid=21345)
VSFM (ccwu.me/vsfm/)	**Ecosynth** (ecosynth.org/)	**Farm Hack** (Farmhack.net)	**Net Carbohydrate and Protein System** (Cornell) (cncps.cornell.edu/)
CHDK (chdk.wikia.co	**Drupal** (drupal.org)	**GreenStart** (Greenstartnh.org)	**USDA RUSL2**

m/wiki/CHDK)			(fargo.nserl.purdue.edu/r usle2_dataweb/RUSLE2_I ndex.htm)
MultiSpec (engineering.purdue.edu/~biehl/ MultiSpec)			

Figure 43 – Key communities, organizations and tools. Three categories and multiple examples of open source communities and tools that provide a foundation for environmental observation and analysis.

This section will review the current state of university and commercially distributed low cost remote sensing research and put participatory action research, such as Public Lab and Farm Hack efforts, in context. These communities provide the foundation upon which future adaptive management APIs may be constructed. The structure and technical architecture is explored within the chapters that follow.

Low Cost Aerial Imagery Indicator Validation

The focus of this technical systems analysis is to present a replicable framework to calibrate image analysis methods that can distinguish species composition and abundance, as well as other environmental conditions in agricultural plots using aerial imagery. The analysis covered in Chapter 11-12 will focus on using aerial imagery which can be rapidly produced with consumer grade cameras and low cost balloons and hobby aircraft and compare the remote sensing outputs with ground truth biomass, species and soils data collected conventionally by hand from quadrats placed at random within the field trial plots. Hand charting of vegetation in quadrats, which was used for both chapter case studies, is a very time consuming and tedious method, but is the standard method used to collect cover estimates in the field. Software tools have already attempted to speed up the process and standardize the measurement process so that results are more uniform and

reflective of the condition of vegetation growing on a site (Johnson, 2009). If the process can be automated, the social, environmental, and economic implications of lower cost and applied research methods integrated into management practices could be dramatic.
The following is a description of the primary steps for adaptive feedback and remote sensing validation which include aerial platforms, imaging and telemetry, ground truthing methods, ground sensor technology, post processing, collaborative publishing and reporting.

The architecture, illustrated in Figure 53, shows the potential for data portability throughout a workflow generated by low cost remote sensors, processed through third party environmental models, and then published back to different audiences in appropriate views to enable both accessibility and control of data throughout the process.
As discussed in Chapter 1, producing good data and analysis is not enough to accomplish effective adaptive management at a landscape level. The data must be exportable, portable, and interpreted into various forms to become accessible to different audiences.

Figure 53 illustrates the data pathways through functional transformation based on linking independent web applications through coordinated standards and Web APIs. The process starts with a management data API feeding into many potential environmental data APIs that are, in turn, picked up through multiple environmental model APIs and decision supported APIs. The final leg of the journey back to managers is through "Views" to make the data available in accessible and useful formats and resolutions. Within this networked data structure, the data can be accessed "where it is" rather than needing to be archived, centralized, and controlled.

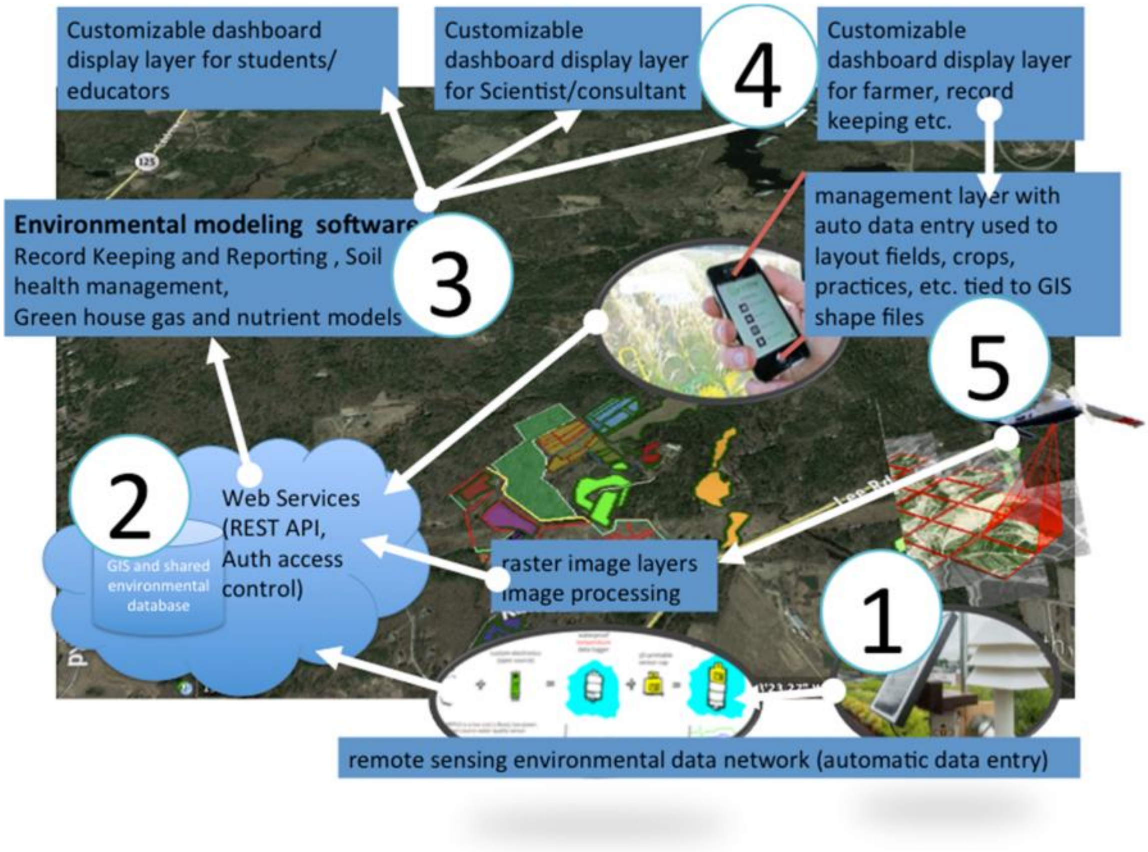


Figure 44 – Social and technical systems expressed as software. Landscape scale model that expresses the workflow and application of the adaptive management feedback model shown in Figure 25, Chapter 5. The data flows from sensors (1) and observations into logs which can then be made accessible through APIs (2) to add value in external environmental models (3), which create value added feedback customized for appropriate audiences (4), which in turn can be used for adaptive management (5). The process also represents a technical flow of the Physiocratic process overlaid on Mirabeau's Tree illustrated in Figure 28, Chapter 5.

The environmental data APIs and management data APIs are particularly valuable steps and have many standards, tools, complexity and support communities behind them to make data flow possible and accurate. To make the flow possible, the structure requires relationships and trust built with every transaction, illustrating the importance of the social structures covered in Chapters 1-5. The technical workflows illustrated here are adaptive, emergent, and to be successful must be generated, by definition, as a byproduct of collaborative decision-making.

Aerial Imagery Platforms and Data Collection Methods

Much of the field of agricultural remote sensing is a parallel progression to the techniques and processes that were developed for satellite imagery for land cover analysis at the regional landscape level (Laliberte et al. 2011). The same techniques are now being applied at a higher resolution at a field and plant scale with the assistance of greater distribution of technology and processing power.

There are many methods for positioning sensors for aerial imagery and remote sensing (Thessler et al. 2011). Kites, balloons, fixed wing, rotary wing, and others (hybrid, blimp, powered kite etc.) are examples used by the open source communities profiled within this study.

A literature review from Thessler et al. (2011) also identified related sensor applications that integrate with UAV data collection including growing conditions, plant protection, irrigation, yield sensing, and mapping during harvesting, nitrogen management and soil, weather sensor network. A survey of Thessler (2011) and commercial imaging services and UAV providers including Precision Hawk (precisionhawk.com) and Agribotix (agribotix.com) identifies additional agricultural indicators potentially generated through image analysis are as follows:

- Crop type
- Plant count
- Soil type
- Soil moisture
- Growth stage
- Biomass
- Forest health
- Disease detection

- Invasive species identification and quantification
- Canopy cover
- Leaf area index
- Plant height
- Nitrogen deficiencies
- Plant health
- Yield monitoring
- Land cover mapping
- Carbon mapping
- Irrigated land mapping
- Impervious surface mapping

Many of the indicators above can be generated using imagery in the visual spectrum, however, customized sensors can increase accuracy by focusing on particular color bands rather than on the full spectrum which can also reduce post processing time.

As methods are developed and validated they will continue to be published to the creative commons through Farm Hack, Google Earth, and other knowledge sharing communities. Publication is crucial to achieving the wider goal of improved quality and reduced cost of environmental monitoring for adaptive management and research purposes.

Linking imaging with ground-based sensing does not eliminate the need for traditional research gathering methods, but *enables far more value to be gained* because every validated ground-based observation can be used to improve spectral/image libraries and environmental models. Each improvement to imaging systems and validation enables more accurate observations at greater frequency and lower cost than the individual conventional observation.

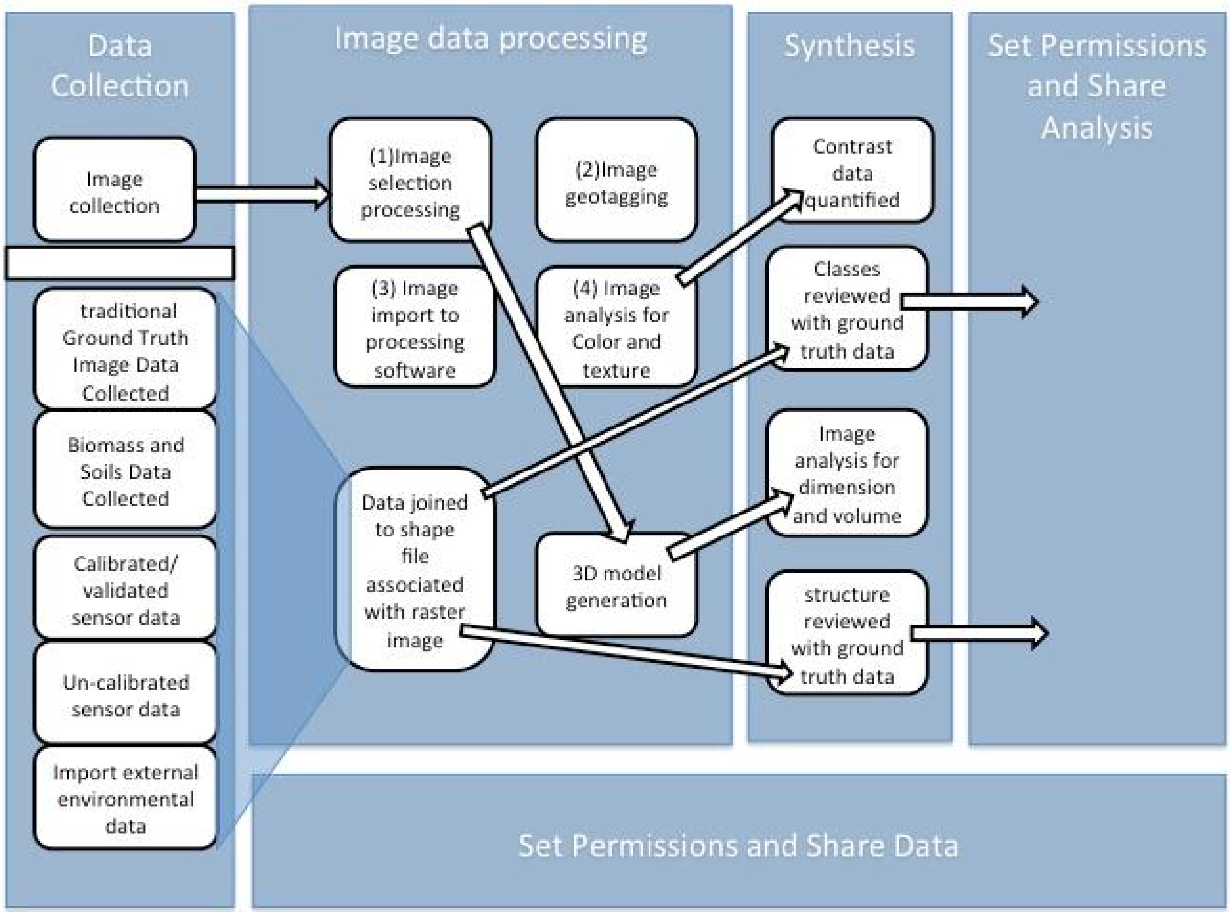


Figure 45 – Workflow model of aerial imaging post processing illustrating the relationship of the functional tools and process of data collection through to data sharing and web publishing. The particular tools used to accomplish the steps may change and become more integrated to improve user experience. The functional steps represent the logical steps required to create usable feedback from aerial imagery in a web publishable and sharable form.

An alternate workflow involves the direct creation of pointcloud and meshfiles using Visual Structure From Motion (VSFM) and 2-D to 3-D modeling commercial software packages such as PIX4D (www.pix4D.com) and AgiSoft (www.agisoft.com). These packages can function without georeferenced files but also will generate geotiffs for export to other image analysis processes.

Popular Agronomy and Data Portability

Collaborative adaptive management assumes citizen engagement in the process, which emphasizes the importance of the Physiocratic metaphor and framework. In order to generate portable and sharable data, agreements on standards are required, such as those developed by Open Layers, Open GEO and the APIs and data translators that enable portability of data from popular platforms like Google Earth to professional GIS systems like ESRI ArcMap.

The process of cartography and data visualization has taken on new significance in the digital age. The casualness and accessibility of digital maps and geographic information systems now nearly universally accessible also leaves the possibility for abuse through apathy; again, this is why the social context in which tools are used is important. Google Earth, for example, represents a social network that is able to present user-generated content spatially on a representation of Earth that can be imagined, projected, and shared in casual fashion (Farman 2011). The data from aerial imagery and analysis collected and processed for this study are viewable in Google Earth and included as .kmz files in the digital appendix. A more limited version is hosted through a Google widget at the Farm Hack ifarm tool.

Figure 46 – Screenshot of data exported into a portable file that is viewable with free software and web publishable. Through these types of presentations of both images and ground truth data, a wider audience can be brought into the context associated with field trials. The image represents just a few of the many possible ways in which data could be presented to the farmer or other citizen stakeholders and scientists.

The above Google Earth image, prior to being exported as a .kmz file readable by Google Earth, pulled data from .xls, .shp, .obj, .dmz, .jpg, .tiff, .skp and many more file formats. Interdisciplinary data depend on standards and agreements across technical communities to enable data translation for adaptive management workflows to function. The many steps required to produce the image, and the diverse file types and data sources required to produce this type of image highlights the need for more accessible adaptive research and development tools. The complexity associated with the many file types and sources also illustrate the importance of software, and software communities that build the trust that is required for standards setting and data sharing.

The medical research and practice has already applied these types of advanced imaging tools and standards and agreements to leap from Computer Aided Design (CAD) of engineered objects, and Computer Aided Manufacturing (CAM) to the applied methods used to document and operate on biological structures within the human body, and build a system of trust for data exchange. Anyone who has had knee or hip surgery in the developed world has likely experienced MRI machines, and orthoscopic imagery. These machines enable high resolution digital image sharing and interpretation by skilled technicians regardless of physical location; the images and associated health records are also shared with medical professionals based on a series of permissions that protect patient privacy. The medical community also provides other templates for the building of trust in open source research. For example, the Human Genome Project provides a template for a massive collaborative and high profile open source effort (Yu et al. 2007), has led to the dramatic reduction in sequencing costs and therefore increased use for medical diagnoses; open source tools and images applied across similar networks and resolutions have similar potential to improve agro-agricultural understanding and management.

Work completed for this study demonstrates that structure and spectral analysis is possible using consumer grade hardware. Additionally, open source and freely available software can be used to publish and distribute the results using methods that will be leveraged when put into the larger social context of agricultural and agrarian clubs described in the second section of the dissertation. The imagery and analysis performed for this study document the current state of the workflows required and bridge many communities. The workflows also illustrate the potential for modular construction that is possible because of the open source nature of the components.

Remote Sensing of Plant Characteristics

As discussed in Chapter 1, there are many indicators that can be developed through imagery; plant growth and health are appealing targets for many reasons outlined within this chapter. In particular, imagery is non-destructive, inexpensive, and creates extraordinarily rich datasets, and could lead to faster detection and analysis methods for plant characteristics supporting reduced manual data acquisition costs. The downside is the inductive and computationally intensive processing required to generate quantitative indicators from images. This chapter provides a brief summary of the current state of remote imaging of plant characteristics.

Plant phenotyping has even been shown possible with this technology (Busemeyer et al. 2013). Stabilizing algorithms for video cameras can be integrated for inter-row navigation and platforms for plant characteristics such as biomass, leaf area index or nutrient status to provide information about the current status of the plants, which hints at growing conditions within the field. Faster detection and analysis methods for plant characteristics can support the reduction of manual work for data acquisition (Graeff et al., 2006).

Crop canopy reflectance and temperature sensing for nitrogen or water stress detection in combination with an ultrasonic sensor for crop height assessment has also been tested (Zecha et al. 2013). Multispectral remote sensing applications from UAS are reported in the literature less commonly than applications using visible bands, although light-weight multispectral sensors for UAS are increasingly being used (Laliberte et al. 2011). Lelong et al. (2008) showed that the quality of spectral ranges reached by standard digital cameras is suitable for remote sensing and that data preprocessing is quite effective. Hunt Jr. et al. (2010) used a filter for red light on several digital cameras without a near infrared (NIR) blocking filter on a UAS, similar to Public Lab's infragram approach (Hunt, Jr. et al. 2010). They found correlations between green normalized difference vegetation index (gNDVI) and leaf area index (LAI). Rabatel et al. (2012) used a single standard digitalRGB camera for aerial field imaging at low altitude (Zecha et al. 2013). They also replaced the internal NIR blocking filter by a low-pass filter, for which Public Lab's filter kits provides instructions. Zarco-Tejada et al.'s (2012) UAV results showed that crown temperature and chlorophyll fluorescence were the best indicators for water stress detection (Kelcey and Lucieer 2012).

Root nodulation size and leaf color indexes are already established as proxy indicators for nitrogen fixation in legumes and soil root color analysis and structure documentation (e.g., nodulation color) has been explored (Gwata et al. 2004; Vollmann et al. 2011). Leaf photosynthesis and rhizomial nitrogen fixation are the two metabolic processes of importance to legume growth and development. These processes are closely related to each other, which also provides an example application for digital documentation of visual indicators of biological processes (Vollmann et al. 2011). Such approaches illustrate the necessity of validation and of a more automated analysis of plots that can quickly and inexpensively screen results through image analysis workflows.

The same techniques illustrated at the field plot level can also be applied at the watershed level or to the plant or plant structure level. For example, the same work flows that are used to document entire fields or landscapes, can also scale down to document individual plant structures. The exchange of data, the files, the software and the permissions, standards and agreements are the same, regardless. Figure 47 illustrates a 3D model created from 2D digital images using the same technique used in field level work, but for plant level documentation. This illustrates that in addition to the landscape and field level analysis, the same methods may also be applied to smaller scale plant structure documentation to enable the exchange of higher resolution observations. This image of an experimental hay bale raised bed, used free on-line software, and produced a geo-located 3-D mesh model which can also contain associated metadata within the file.

Figure 47 – Images created by 2D images transformed into 3D models, illustrating that the technology, workflows, data standards and tools can be used to document and share environmental observations and data at multiple scales. The structure of squash plant leaves, color and texture analysis and other high resolution data can be exchanged in the form of digital files to enable observation, quantification and structural analysis and aggregation of many detailed observations, at many scales, into larger analysis that may be emergent and unanticipated at the point of data collection.

Post Processing Methods for Species ID

Post processing methods for species ID are rooted in machine learning approaches and case based logic (Koh and Wich 2012). These methods are rooted in developing large quantities of case data to learn from. The accuracy and indicator validation in both computer and social, participatory learning is an iterative process. This validation process is generalized within the adaptive framework identified in Chapter 3.

As discussed in Chapter 3, there are many indicators that can be visually quantified. The crucial next step in the workflow is to translate images into rich data sets through the post processing process. "Rich datasets" refers to the large amount of quantitative data generated through a pixel-level analysis which also has associated meta data with it, including but not limited to location, time, altitude, barometric pressure, temperature, camera settings. In the generalized adaptive management framework is a process of associating values and data contained within the imagery into context by relating that data to existing values within the database. The networked effect of the data in context then becomes more valuable to all users of the data base by further increasing the context for interpretation. Fully exploring all of the approaches to post image processing is beyond the scope of this study. However, understanding the current state of imaging and analysis, limitations, and technical trajectory is crucial to the broader system's study.

There are many methods for classification analysis used to identify species, plant structures, or other features that will need to be evaluated and adapted to higher resolution imagery, deeper open libraries, lower cost processing and more accessible workflows. These techniques include but are not limited to:

- Unsupervised Classification
- Supervised Classification
- Object-based Classification
- Change Detection
- Target Detection/Extraction
- Spectral Mixture Analysis
- Wavelet Analysis
- Texture Analysis

Unsupervised Classification methods generate a map with each pixel assigned to a particular class based on its multispectral composition. The number of classes can be specified by the user or may be determined by the number of natural groupings in the data. The user must then assign meaning to the classes, and combine or split classes where necessary to generate a meaningful map. Successful uses include major vegetation types, distinguishing native vs. invasive species cover, vegetation condition, and land use change.

Supervised Classification methods are used to generate a map with each pixel assigned to a class based on its multispectral composition. The classes are determined based on the spectral composition of training areas defined by the user. Supervised Classification has similar uses to Unsupervised, but with an added step in the workflow.

Object – based Image Analysis (OBIA), a technique used to analyze digital imagery, was developed relatively recently compared to traditional pixel-based image analysis (Burnett and Blaschke 2003). While pixel-based image analysis is based on the information in each pixel, object-based image analysis is based on information from a set of similar pixels called objects or image objects. More specifically, image objects are groups of pixels that are similar to one another based on a measure of spectral properties (i.e., color), size, shape, and texture, as well as context from a neighborhood surrounding the pixels.

Change Detection's goal is generally a layer or image that highlights areas that have changed between two (or more) time periods and the direction and magnitude of change.

Target Detection creates output in the form of a map of the spatial distribution of the target object, species or cover type. Using sub-pixel techniques, the software estimates the abundance fractions of targets contained in each image pixel, rather than simply labeling each pixel to one cover class as in classical image processing.

Spatial Wavelet Analysis (SWA) has output that is an ASCII file listing the diameter and spatial location (X and Y coordinates at the object center) for objects detected by the wavelet analysis algorithm. GIS software is needed to display the output data spatially. All objects are represented by a circle when the Mexican Hat wavelet is used, however other wavelet shapes could potentially identify objects of different shapes.

Spectral Mixture Analysis (SMA) is a technique for estimating the proportion of each pixel that is covered by a series of known cover types. It seeks to determine the likely composition of each image pixel.

Texture Analysis or texture mapping is a common method for delineating surface features that cause localized variations in the brightness and other spectral properties of the image, including shadowing. Texture is the spatial distribution of tones across the pixels of remotely sensed images, providing a measure of tonal variability.

As with most systems analysis, the results and the power of the tools are amplified when they are used together to generate a richer, more dense data source.

Technology Workflow and Illustrated Field Studies

Chapter 11& 12 Introduction to Methods and Structure

The purpose of the following two chapters is to observe and evaluate the technical process of data collection for computer aided inductive analysis, relate it to deductive methods, and draw conclusions about the status of existing tools for providing meaningful quantitative feedback within the participatory system described within the first ten chapters. Both case studies presented in these chapters represent field trial approaches aimed at answering questions in agro-ecology but also represent projects that could be replicated in distributed on-farm trials. Future design of on-farm research depends on the quality, cost and ease of use of the observation and analysis technology. The case studies also serve to illustrate applied workflow within context of the framework used for data acquisition and analysis as the required steps prior to communication through inductive analysis and adaptive management. Both chapters will focus primarily on agricultural plot trials that were established within a conventional randomized block designs. These cases illustrate the complementary aspects of inductive data gathering to deductive analysis as well as highlight challenges and limitations. The outcome of the chapter should be an understanding of the current technological capacity to approach environmental quantification within the social and biological outcomes derived from increasing accuracy, participation, and accessibility and lower observation and analysis costs. The current state of workflows used for analysis in this context is relevant, not only in the context of the quality of the environmental data output, but in the accessibility, cost, flexibility, social context and cultural acceptance of the methods. The case studies serve as an example of the importance of leveraging conventional agricultural research to improve participatory remote sensing approaches that are dependent on validation and calibration using deductive approaches.

Chapter 11: Low Cost Aerial Species Analysis of Forage Crops

Introduction

Here, a portion of a field experiment illustrates the process of evaluating and improving remote sensed imagery of agricultural research plots taken from consumer grade equipment for accurate species differentiation. The goal of the case study is to document and evaluate a *workflow* required to calculate and validate percent cover analysis of a highly diverse forage crop analysis. The field portion and plot analysis were chosen to address the potential for remote sensing species identification and biomass response of amendments. The underlying agricultural plot trials provide examples of the ground truth species analysis, soil conditions and treatments. This chapter also focuses on the post processing workflow and validation process for aerial imagery analysis. The analysis of the field data and associated imagery is used to study the current accessibility and accuracy of species identification through image analysis in order to draw broader conclusions about the role of image analysis, and current limitations for species identification and quantification in the adaptive management framework identified in Chapter 4. A portion of the field trial ground truthing data was published in 2014 (R. G. Smith & Cox, 2014) in a paper focused on yellow rattle response to woodash treatments. The results and reporting are also published on Farm Hack and on NE SARE websites (Cox 2012b).

Imaging Platform and Camera Setup

The imaging portion of this experiment used balloon mounted Canon S495 12+megapixel point and shoot cameras mounted on a string harness tethered from 10' to 1000' running open source firmware called CHDK (Canon Hacker Development Kit). The scripts are downloadable on Farmhack.net, DIYDrones.com and many other open source mapping community web sites. The software enables full control of exposure, white balance, automatic triggers and intervelometer scripts that enable timed imaging (e.g., a picture every 4 seconds) and remote control of camera functions. The aerial imagery presented in this study was collected during balloon flights in May, 2012. All images from the plot and associated meta-data are included in the digital appendix.

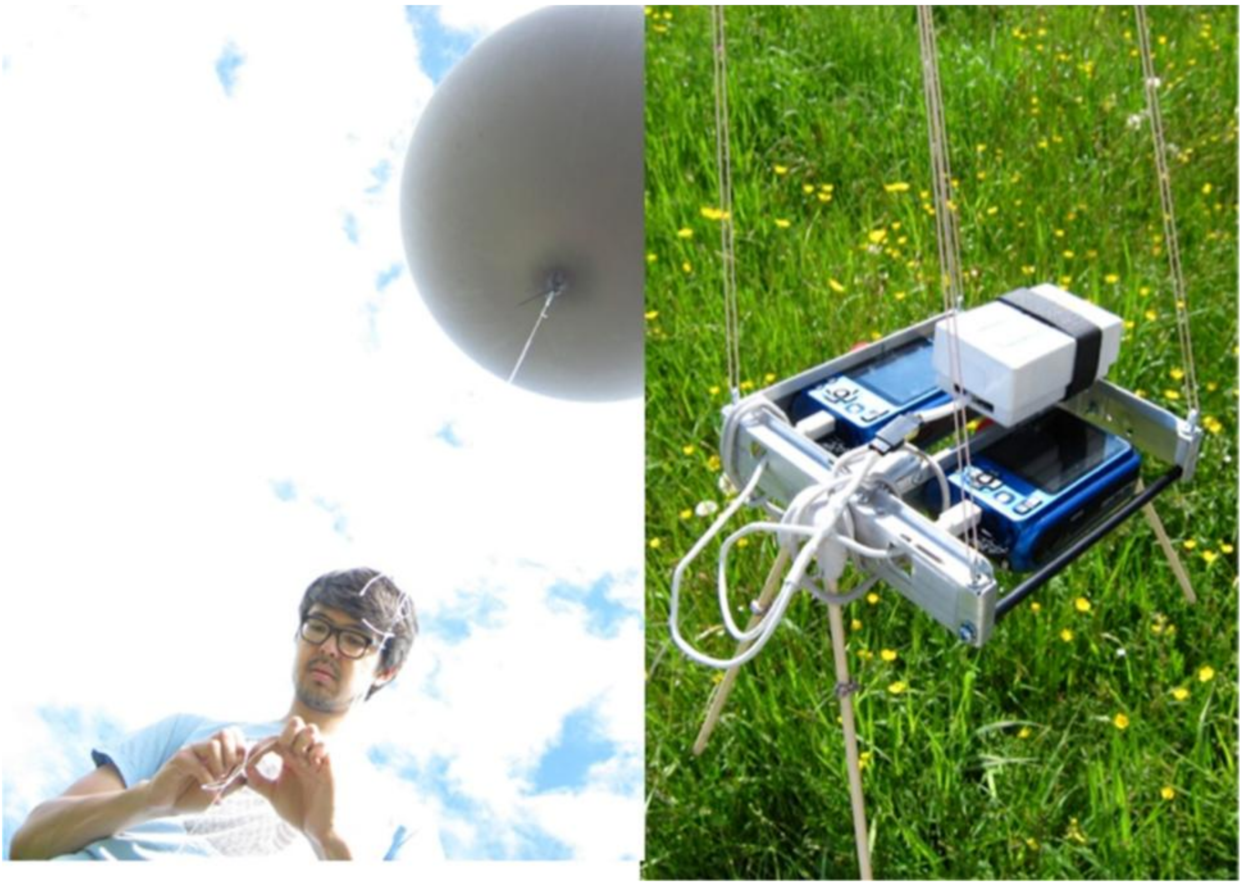


Figure 48 – Cameras are attached to a harness and then to the balloon tether. The dual camera NDVI camera rig and trigger enables simultaneous images from the visual spectrum and near infrared. Open source software then pairs the images during a post-processing step. The hardware required, including helium, can be purchased for a few hundred dollars.

The no-till hairy vetch trials also provided the social basis for organizational meet-ups between Public Lab and GreenStart and for the creation of the iFARM collaborative covered in Chapter 4-6. The collaborative work of these groups provided the foundational technical approach discussed within this section. The output of the combined data and imagery is illustrated in Figures 49-51. These images are the output of the workflows explored within this study, but as static images of an interactive tool and process, are crude approximations. The interactive .kmz files can be accessed from the digital appendix to more fully illustrate the capability of digital publication and exchange of agricultural observations.

Figure 49 – Geo-located stitched aerial images of no-till vetch plots published to web based GIS services such as Google Earth illustrate an alternative method to communicate experimental design, execution and results.

Field Measurements - Ground Truth Data Collection Methods

The field trial portion of this experiment using the biomass analysis of hairy vetch was measured on June 12, 2012, approximately 37 weeks after the amendment treatments were applied and when the majority of individual hairy vetch plants were flowering. Biomass was measured by harvesting all individuals of the plant community rooted within two randomly placed 50 by 50cm quadrats within each treatment replicate. Harvested biomass was sorted to species (except grasses) and dried to constant weight at 60° C and weighed to the nearest 0.01g. Data from the two subsamples were averaged to obtain a plot-level measure of hairy vetch and remaining plant-species biomass. Soil biochemical properties were measured in each plot on June 14, 2012 (two days after the hairy vetch and plant community biomass were sampled). Soils were collected by taking four soil cores to a depth of 15.2 cm from within the portion of each plot that was harvested for aboveground biomass. The soil samples, along with samples of the commercially available wood ash and bio char used in the experiment, were analyzed for pH organic matter (loss on ignition at 500° C) and nutrients by Agro-One Soils Laboratory (Ithaca, NY) (Smith 2014).

The data for this case study are in the form of digital imagery and meta-data files that were generated through the post processing. All associated digital data are included as part of the digital appendix.

Figure 50 – A screenshot of the treatments published to Google Earth. The raster image of plots can then be associated visually with the associated treatment and shared with casual observers of the project. The static nature of this image, however, does not illustrate the interactive nature of the tool, which also enables the user to zoom into observe detailed plant growth of each plot.

Figure 51 – In addition to labels and data tables associated with each plot, the ground truth data can also be overlaid and indicated by color transparencies to enable the visual identification of patterns. In this image, the density of the green indicates yield, with light green indicating lower biomass. The screenshot of does not communicate the interactive nature of the tool, which also enables zooming in to individual plots, and the ability to click on each plot to view the data behind the layer. The interactive .kmz files can be accessed from the digital appendix to more fully illustrate the capability of digital publication and exchange of agricultural observations.

Illustrated Workflow for Quantified Image Analysis

The images within each plot were analyzed at the pixel level for color range, color consistency, color density, and contiguous areas of color ranges. The objective of these analyses was to graphically differentiate between plant species and then validate the image analysis with biomass data collected from that same plot. The iterative analysis of each plot enables a regression process to achieve a "best fit" and result in a visual analysis model calibrated to traditional ground based data collection methods which can create a validated and automated workflow. The replicated block design and mowed alleyways also provide examples of factors that facilitate post image processing and analysis.

The illustrated workflows in the following section can be completed manually. However, the goal of the documented workflows is to identify advanced planning steps for improved field preparation to enable more automation of the basic processing steps.

Alternate workflows are possible if 3D mesh is created first with georeferenced images. A geotiff can be exported then shape files used as a mask to select raster image for plot analysis. The baseline visual spectrum image was georeferenced and imported into Google Earth. This layer will be imported as a .klm file to assist with georeferencing higher resolution images. The number of images should enable more than a 50% image overlap to achieve the highest resolution and greatest accuracy.
The .kml file is used to define polygons around each plot. Once each plot has been geographically located, each polygon's properties are populated with the associated soil and biomass data. These data can be imported from from .xls, or .csv table format into the plot layer polygons with a join to the plot ID prior to export as a kml file (or any other web publishable format).

After plot data population and geolocation, raster image layers from the aerial photographs were imported into ArcMap (ESRI.com). The images were then selected by geolocated plot for individual graphic analysis. Several approaches were used in both raster and converted vector layers analysis within ArcMap. Although the workflows that generated the images were documented in ArcMap, QGIS (qgis.org) workflows would be similar.

For this project the “best fit” with the tools available within ArcMap was a combined supervised and unsupervised method. This project started with an ISO Cluster Unsupervised classification in the Image Analysis tool box. The output of that analysis yielded a number of classes that were then manually identified. Each pixel was then assigned to a class. The number of classes assigned is user determined and an arbitrary process without ground truth calibration to identify visual signatures used to identify species variation. The user-chosen classes may or may not correspond well to actual land cover. In this case, although the calibration of the class delineations was not possible, the description of the work flow, which is the primary purpose of this study, remains valid. After the delineation of class boundaries, meaningful labels were assigned to each class. In this case, although not calibrated, the classes were assigned to vetch or not vetch and given a color to communicate the distinction and class boundaries. Figure 52 illustrates the output of this process.

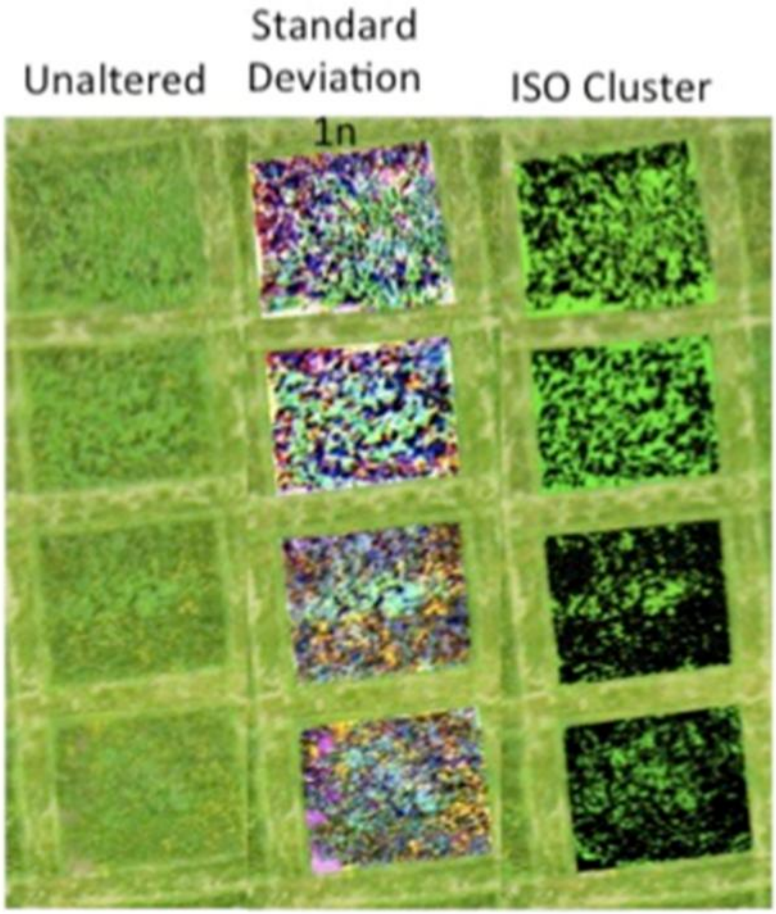


Figure 52 – Species quantification using ISO cluster analysis, which uses the classification of individual pixel color to identify boundaries. In the four ISO cluster plots, green represents vetch and black represents not-vetch. The number of classes and color boundaries is set by a guided process, and without ground truth image calibration data the process is arbitrary. The image is included as an illustration of the output of the workflow, and to show the value of ground truth data in creating meaningful quantification from image analysis and the complexity of creating an automated workflow.

The above image illustrates the process of image classification through an ISO cluster analysis, which is used to group color classes together and use the classification to quantify individual species percent cover within the plot. Other types of analysis, both guided and unguided may produce a better fit, however, without ground truth data, the selection process is arbitrary. Figure 52 is included as an illustration of the output of the workflow, and to illustrate the value of ground truth data for creating meaningful quantification from image analysis. It also illustrates the complexity of creating an automated workflow. Because the data associated with the percent cover calculations generated through this process was generated through arbitrary determination of class boundaries without ground truth values, or a library of ranges to reference for the boundary of values associated with hairy vetch imagery, the data generated from this image is not meaningful other than to evaluate the workflow and conditions required for future analysis to be meaningful.

Discussion

To realize the full potential of participatory remote sensing will require many more trials that generate greater large digital libraries of images and ground truth data needed for machine learning. As modeling methods and neural network processes and spectral and textural libraries improve and are coupled with Visual Structure from Motion and other 3D modeling methods, the accuracy of this type of process will improve, while also becoming more automated.

As is illustrated by the discussion of Figure 52, the current limitation with unsupervised classification is that it often results in too many land cover classes, particularly for heterogeneous land cover types, and classes often need to be combined to create a meaningful map (Ghorbani et al. 2006). In other cases, the classification may result in a map that combines multiple land cover classes of interest, and the class must be split into multiple classes in the final map. Unsupervised classification is useful when there is no preexisting field data or detailed aerial photographs for the image area, and the user cannot accurately specify training areas of known cover type. Hybrid classification may be used to determine the spectral class composition of the image before conducting more detailed analysis and to determine how well the intended land cover classes can be defined from the image. The higher the level of supervision, the more accurate the analysis; supervised and unsupervised classification are both pixel-based classification methods, and may be less accurate than object-based classification (Karl and Maurer 2009).

In addition to the uncertainty introduced by the class selection process and choice of analytic tools, percent cover calculations do not necessarily correspond well with biomass ground truth data (Mischler et al. 2010; Teasdale et al. 2012). The growth patterns of vetch exacerbate the measurement challenge because of the viney aboveground plant architecture which tends to grow horizontally across other plant species. The image analysis results, however, may yield a more accurate assessment of forage species performance when combined with 3D biomass volume calculations. Combining the image analysis methods covered in Chapters 11(color analysis) and 12 (structural analysis) shows promise and is identified as a next step in Chapter 13.

Case One - Conclusion

This case study does not attempt to provide an exhaustive survey of approaches. Rather, it tests the current state of the agro-techno-social systems and illustrates a representative workflow by applying the techniques to a field trial. The field trial itself, is representative of the type of research question that would be appropriate to incorporate into an adaptive management and Physiocratic soil health framework. The trial also represents the starting point for the generation of an expansive on-farm, inductive research model. Because the focus of this case study is on illustrating the work flow and process, rather than on particular insights into biological systems or the particular tools used to illustrate the process, the outcomes and conclusions are in the form of recommendations for future refinements and improvements of the workflow and tools. Future work will be required to develop field protocols for ground truthing percent cover calculations and for using whole plot biomass sampling for ground truthing the percent species mix in relationship to percent cover. In addition to ISO cluster analysis, many other commercial GIS tools will also need to be tested to improve image analysis. Some examples of these tools in packages such as ArcMap include geographically weighted regression, con spatial analyst, zonal histograms, zscore rendering, and generate spatial weights matrix. The model's spatial relations might also be explored using the exploratory regression tools now available through the ESRI Spatial Statistics Tool Box. Image calibration libraries would also facilitate exploratory regression analysis between species biomass, percent cover species analysis, soil analysis and treatments with color species analysis, and other texture or color analysis with other ground collected and treatment data.

Many of the other techniques and tools for image and texture analysis have unique challenges that will need to be evaluated and validated, a process which would benefit from the distributed, participatory elements discussed in Chapter 5. That process is highly dependent on social systems, coupled with backbone network facilitation and guidance and evaluation by experts to populate image libraries with associated ground truth metadata.

To generate effective indexes will require the evaluation of multiple approaches that are analyzed with much larger data sets that also include calibration data. This type of analysis is beyond the scope of this dissertation, but the road map to generate the data sets through participatory action is not. This case study shows the limitations of uncalibrated images, and illustrates the importance of ground truthing and the supporting social networks and computationally intensive inductive methods required to validate and test multiple post processing methods and workflows. The communications technology to provide every citizen the equivalent evaluation skills of an experienced field technician exists as presented in Chapter 5; however, without the collaborative nature of large data sets, the local data sets can be used as qualitative indicators for management. In order to draw larger inductive conclusions and formulate more precise lines of questioning (e.g., expert evaluation and recommendation by smartphone), a substantial social, collaborative, and participatory effort is required.

The Physiocratic social framework proposed by this study provides one of many possible social contexts to achieve the feedback required for collaborative adaptive management. However, to assemble collaboratively accumulated data libraries that are necessary to realize the promise of rapid, cheap, accessible and accurate observation tools, the primary challenges are still social in nature. Collaboration and shared values of the social system are crucial elements to developing these techniques as quantitative indicators.

Some specific field protocol approaches may also improve the post processing work flows. Examples of ideas that were generated by members of the iFARM team include the use of GIS located calibration cards and aerial targets with known color and reflectivity to facilitate pattern recognition and fine-tune post processing. Development of and testing these methods would require ground truth and validation processes that benefit from the participatory approaches covered in Chapter 5.

Chapter 12: Low Cost Aerial Biomass Volume Measurement

Introduction

As discussed in Part I, Chapter 4, rapid, low cost and accessible feedback is crucial to the viability of adaptive management. Chapter 12 continues the focuses on image analysis as an approach to create immediately interpretable and meaningful values generated by low cost cameras. This chapter examines an alternative, but more quantitative, approach and asks if volume calculations from three dimensional point clouds generated by similar consumer grade cameras can be used as an indication of plot biomass and crop yield calculations. This investigation primarily used data collected from a field trial set up to investigate reduced tillage methods in grain corn crops completed in 2013, but also uses some of the data from the previous no-till hairy vetch trial. All images from the plot and associated meta-data are included in the digital appendix. The results from this trial were also and reported and published on the Farm Hack and on NE SARE web sites (Cox 2014).

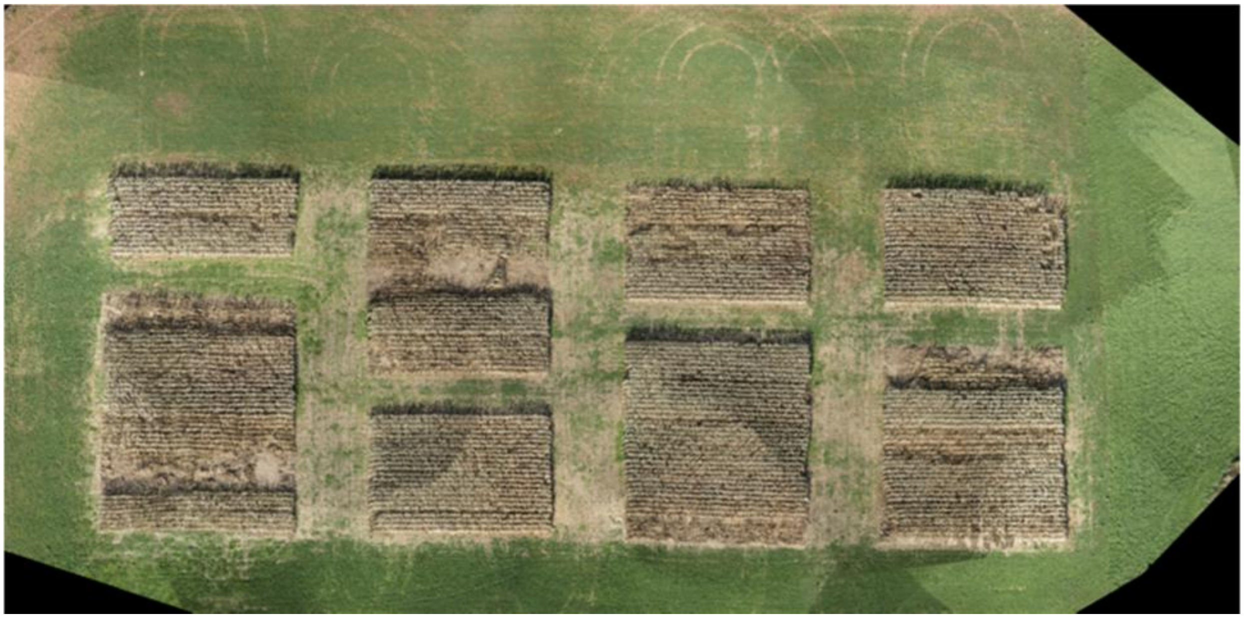


Figure 53 – Representative Geotiff created from multiple images taken by low cost fixed wing UAS. This image and the digital data associated with it illustrate the output of the process and an interim step in color and structure analysis. The variation in color across the plots and fields illustrates one of the challenges for image calibration. The 3D model generated from these images is interactive and available as part of the digital appendix.

Materials & Methods
Imaging Platform and Camera Setup

This case study and illustrated workflow illustrates the use of open source hardware and software tools typical of those described in Chapter 10. The images used for analysis were taken with a consumer grade point and shoot camera mounted UAV with a total hardware cost of less than $500. The bill of materials for the hardware setup is provided in Chapter 4, Figure 21. The images made of this trial were taken with a 12 megapixel A2200 Canon camera running open source firmware called CHDK (Canon Hacker Development Kit) mounted on a stock Hobby King Bixler2 airframe running an APM 2.5 3D robotics autopilot and controlled with Mission Planner software which also provided flight data telemetry. The assembly and sourcing of components and software is fully documented and supported by the open source communities identified in Figure 43. The CHDK software enables full control of exposure, white balance, automatic triggers and intervelometer scripts that enable timed imaging and remote control of camera functions. The aerial imagery from UAV flights was collected in June, August and November of 2013. The full datasets, image files and .kmz google earth files with embedded data by plot are included in the digital appendix.

Figure 54 – Illustrates the $600 UAS with Ardupilot 2.5 and 12 megapixel Camera running CHDK used to document the corn plots in 2013.

Post Processing Analysis of 3D Models of Agricultural Plots

Figure 55, below, was generated using MeshLab (http://meshlab.sourceforge.net/). Autodesk's123Dcatch(123dapp.com) was another option for image processing, but did not offer geo-referencing. However, once a 3D model is created, Meshlab can export the file to enable it to be opened using tools such as Trimble Sketchup (sketchup.com), which enables georeferencing models through a Google Earth plugin. Purpose built commercial software tools such as Pix4D(pix4d.com) and Agisoft(agisoft.com) have built-in georeferencing tools. Meshlab, Sketchup, Autodesk 123D, PIX4D and AgiSoft or other similar 3D editing tools enable volume to be calculated from these models.

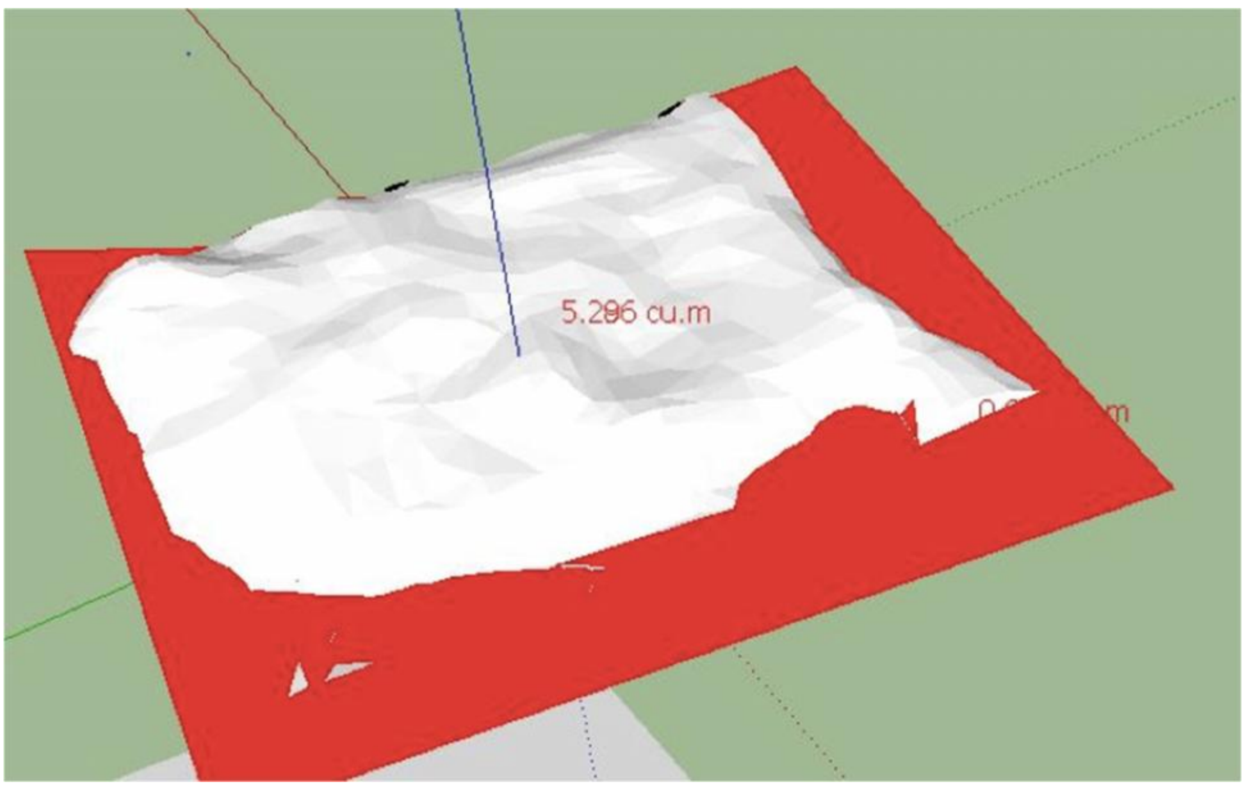


Figure 55 – This image illustrates the variety of tools that can be used to calculate plot volume once the 3D mesh model is created. In this case, Trimble Sketch-up is being used with a volume analysis plugin to "close" the bottom of the 3D model of a plot. The red square represents the calculated ground level. The white portion of the model illustrates the vetch and grass growth. The number indicated in the center of the model is the calculated volume of the plot. These models can also then be 3D printed as an alternative method of observation and analysis.

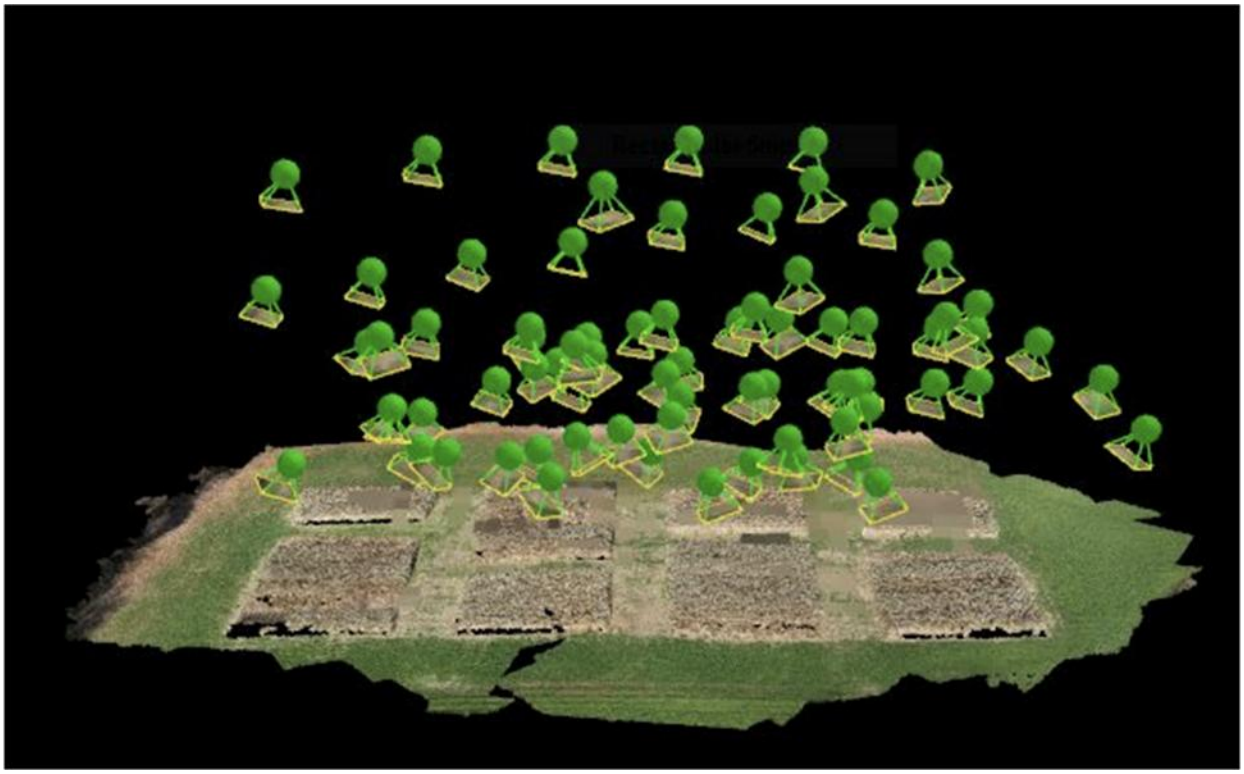


Figure 56 – This image is representative of the many available commercial and open source tools for creation of point clouds and mesh models. The green balls positioned above the 3D model indicate the position from which the 2D images were taken above the landscape and relates them to the 3D model that is was generated from those images. The 3D model can then be manipulated and analyzed to calculate crop height, volume and texture. The screenshot is a static representation of interactive model generated by a representative tool. The model and associated image files are included in the digital appendix.

The same basic approach is automated by Pix4D software using their "stockpile" function.

An analysis of the accuracy of this method follows:

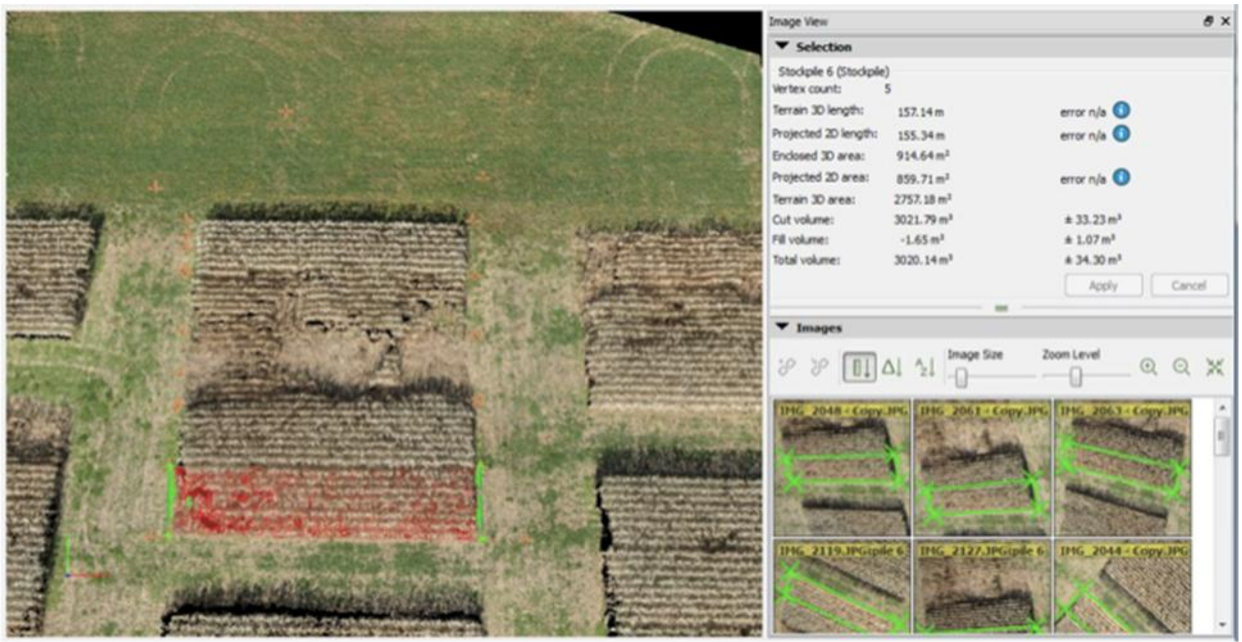


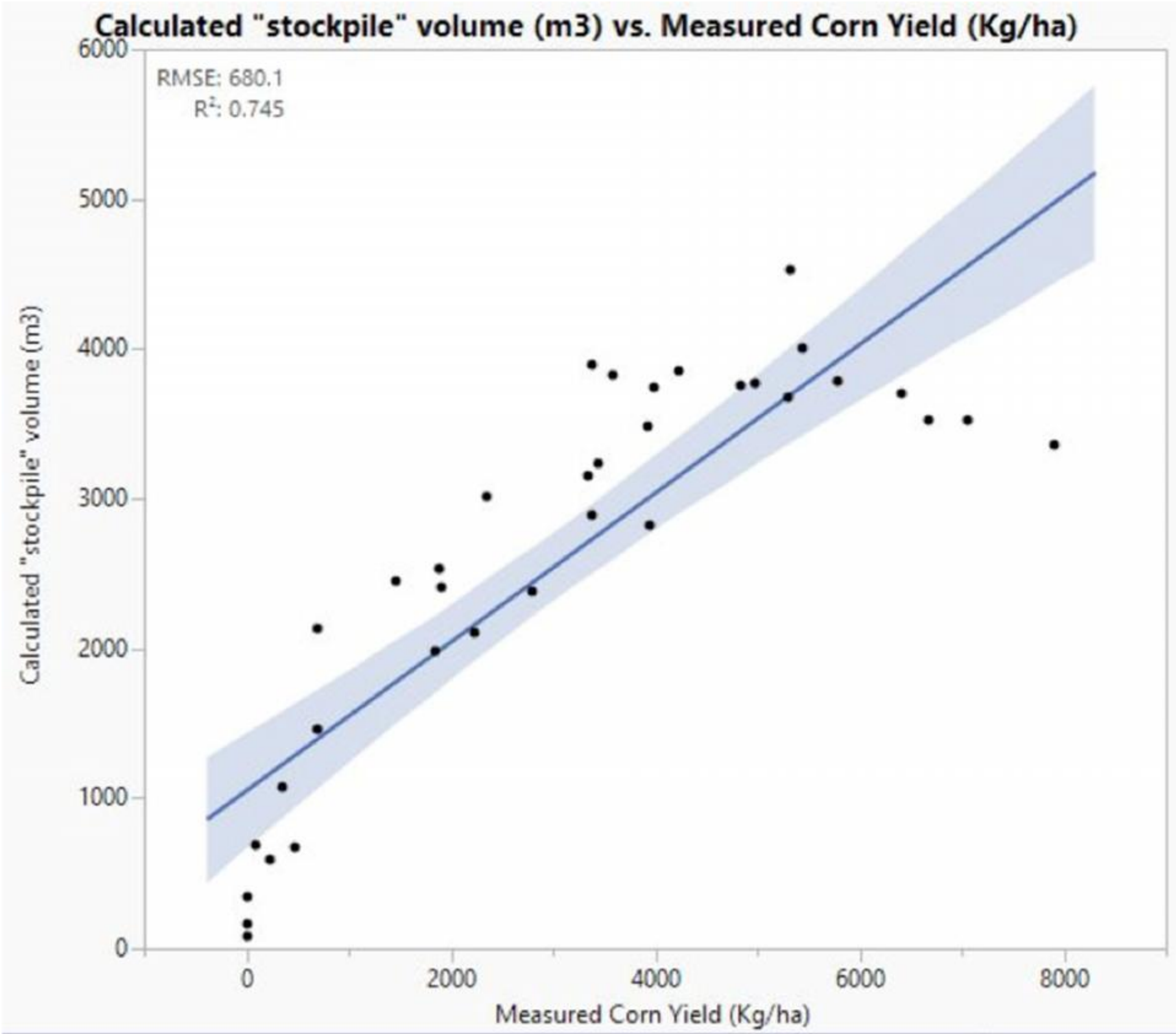
Figure 57 – This screenshot is representative of the basic workflow in using the "Stockpile" tool for volumetric analysis. The grain corn was planted with mowed grassy alleyways between blocks, which provided contrast and reference points to facilitate image post processing and analysis, and enabled the ground level to be extrapolated by the software to create a "closed" mesh model made up of polygons representing a single plot. The volumetric values output by the tool are indicated in the upper right of the screen and the images used to calculate the values are listed in the bottom right.

The PIX4D stockpile tool was used to measure the biomass volume of each plot. It shows the same basic workflow as illustrated above, but automates it with a simple tool that can be used to select a polygon bounded by ground located points, then calculates and fills in the missing planes to create a closed object. The closed object is then used to calculate the volume of that object (plot). Once the 3D model is built and loaded within PIX4D, the volume calculation process takes just a few seconds. Figures 56 and 57 illustrate the workflow and processing required to create a volumetric analysis.

The data for this case study is in the form of digital imagery and meta-data files that was generated through the post processing. All associated digital data is included as part of the digital appendix.

Discussion

The data generated by the "stockpile tool" illustrated in Figure 58 indicates that there is a correlation between corn crop volume and yield. However, more analysis is needed in other crops and crop conditions to develop a valid proxy for yield measurements. The calculated volume values correlated with the manually collected yield data with an r squared of (.745) in a linear fit as illustrated in Figure 57. The results also indicate a higher accuracy at middle level yields and drops off at high or low yields. A quadratic regression improves the fit with an r-squared value of (.930) as illustrated in Figure 58. This interpretation reflects the structural observation of the images themselves. Low yielding plots might have no or very low grain corn but weed biomass will still register as plot volume. At higher yields, the yield increase could be in the form of larger ears rather than increased crop density and height. If the increase in yield is not externally visible in the form of increased crop height of leaf cover density, it would not be picked up by the imaging process.



Calculated "stockpile" volume (m3) vs. Measured Corn Yield (Kg/ha)
RMSE: 680.1
R²: 0.745
Calculated "stockpile" volume (m3)
0
1000
2000
3000
4000
5000
6000
0
2000
4000
6000
8000
Measured Corn Yield (Kg/ha)

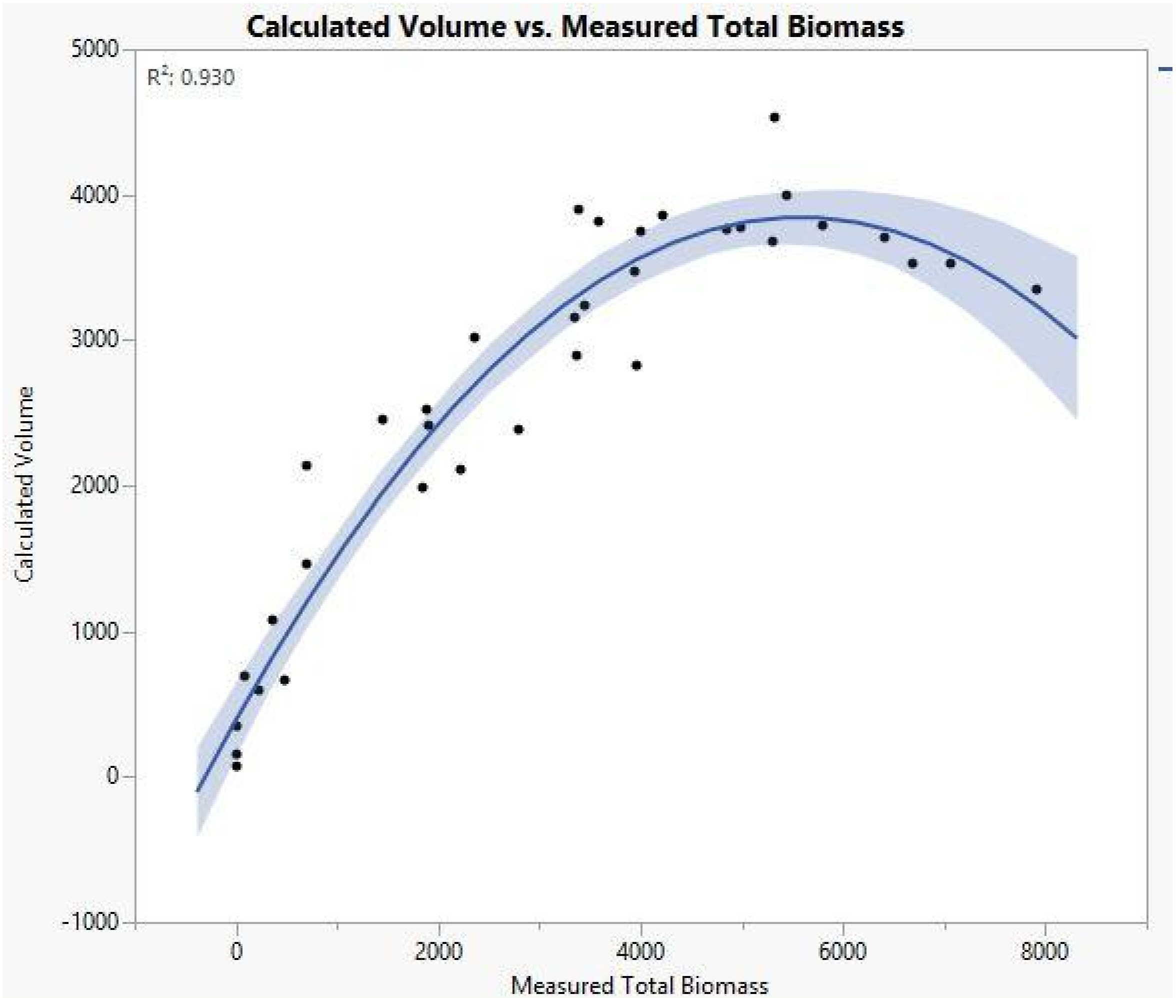


Figure 58 – Volumetric Analysis of Corn plots vs. Measured Corn Yield.

When the same volumetric process was applied to several rows of the hairy vetch plots used in Chapter 11, the volume had very low correlation with the collected biomass as illustrated in figure 60. This contrast is useful to illustrate the limits of this approach to plot analysis in certain species mixes. In the case of the vetch plots, the plots also included perennial grasses. The vetch is not particularly dense, but because of its viney architecture can indicate high on the leaf area index, percent cover, and volumetric analysis, while some of the grasses may be dense and even lodge close to the ground creating a very low volume profile. The difference in accuracy clearly highlights areas for future work and the disadvantages of a volume only analysis. This data is also included in the digital appendix.

Figure 59 – This image illustrates the layering of a 3D model of the no-till vetch plots that has been exported to Google Earth. The topography and texture of the plots is clearly documented, and can be sent as a digital file or published in an interactive form on the web. The image also illustrates the convergence of image and texture analysis with volumetric analysis to describe the outcome of multispecies composition and performance in a field trial.

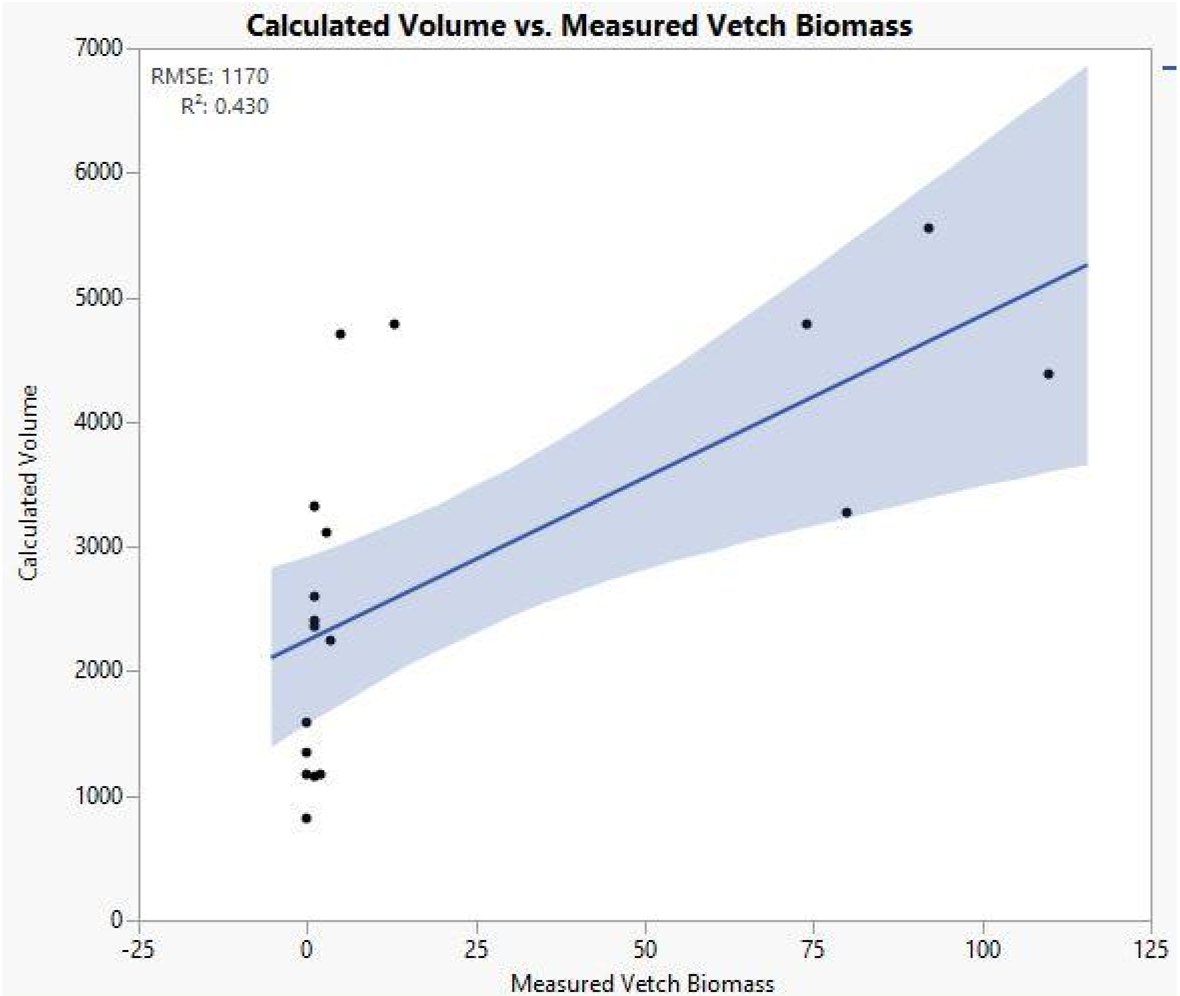


Figure 60 – Volumetric analysis of vetch plot volumes vs. measured vetch biomass.

This method and analysis of both the corn and vetch plots was also aided by the mowed alleyways to provide ground point references and contrast. The corn images and clearly visible rows also made post processing easier. If the same technique were applied on-farm, some consideration for markers would also be helpful in post processing analysis, although historic ground topographic models taken without vegetation, during winter for example, could serve the same purpose.

For large plots that will be harvested with machinery equipped with yield monitors it is not clear that an image based volumetric approach would provide an advantage, however, it does provide the opportunity to do pre-harvest analysis and to track differential growth rates. It also has the advantage of being available as a method when yield monitoring equipment is not available. Imagery can also be taken multiple times a year, and to increase accuracy, and improve resolution to within a few centimeters (Harwin and Lucieer 2012). Further exploratory image analysis using ground truth data for moisture, weed biomass, and soil conditions was beyond the scope of this workflow analysis, but follows the same image post processing workflow and challenges covered in Chapter 11.

A next step in image processing is to more fully employ 3D structure from motion tools such as VisualSFM that enable greater customization of the processing than the commercial closed source products such as Pix4D. VisualSFM is a GUI application for 3D reconstruction (homes.cs.washington.edu/~ccwu/vsfm/). Once crops are modeled in 3D mesh files, many tools are available for digital exchange and translation of the files. 3D printing sites, such as www.thingiverse.com, provide a place to post, exchange, and order prints of the 3D models, which adds to the flexibility and diverse methods for interpreting and exchanging crop data. 3D printing provides an alternative workflow for volumetric analysis. Although not pursued for this study, the files illustrated in Figures 59 and 57 could have been printed, the plots manually cut out, and the volume measured through liquid displacement methods.

Conclusions

The image based volumetric analysis used in this experiment illustrates the promise of low cost hardware coupled with computationally intensive post processing made possible by open source communities. The results illustrate that it is not yet accessible due to the complexity and background work required to calibrate and understand its best uses. However, it also illustrates a trajectory of rapid, inexpensive, and accessible tools that have the potential to offer citizen scientists the equivalent evaluation skills of an experienced field technician. The next steps will require calibration and approaches in different crop and weather conditions, timing, and evaluating the continually changing hardware and software that becomes available almost daily. Even without advances, the data from this experiment provides a template for ground truthing that can already function to build and provide value as broader conclusions are developing. Future work that combines several remote sensing methods together such as combined image, texture with volume analysis is likely to provide a much more accurate field assessment that will certainly be part of future refinements and efforts. While the techniques are being refined, the use of isolated plot trials rather than on-farm conditions is useful and necessary for evaluating the ground truthing and calibration process of the technology. Additional work from the next round of trials will also help to identify the field protocols for plot layout and design that will facilitate the ground truthing process to evaluate image based calculated measurements with other measurements such as yield and biomass. Some examples may be the use image calibration cards and image targets mounted on geolocated corner posts. The advancement in networked sensors could also expand the potential for ground truthing soil, water, and weather sensors. Future trials might also expand manual crop height measurement, which will also be important in the evaluation of other remote sensing equipment Laser distance measurement technology (such as LiDAR), used for altimetry, and contour mapping which is now being offered by companies such as Pulsed Light (www.pulsedlight3d.com) for less than $100.

When used in coordination with yield monitoring equipment this would further improve the calibration library for various crops. Each of these developments will contribute to the future plot design, and effect flight times and improve post processing, and the creation of accessible output layers, exportable to tools such as Open Layers and Google Earth. The iFARM case study, covered in Chapter 9, illustrate that the collaboration and interaction between these methods can be accomplished rapidly and inexpensively through open source community interactions and field trials.

Chapter 13: Summary and Review

Structure of this Chapter

This broad study examined cases and challenges in systems study in communication, complex interactions of biology, culture, and technology. There are inherent challenges in inductive research, because of the lack of bounds and unlimited possible lines of questioning that come about, especially when examining the intersection of complex systems across disciplines. However, that main challenge was also the topic of this study, and substantial progress and broad patterns emerged from the process of developing an approach and meaningful framework to tackle those challenges. This dissertation comes at an exciting time in which observational, analytic and communications technology enables a more full understanding and productive approach to investigating biological systems, but the technology is also emerging at a crucial time to inform culture, which can in turn take action to re-balance the global carbon and other nutrient cycles. However, the question "who has this control of this knowledge and how is it gained?" has many more possible answers now than in any previous time in history. We can now ask of our own culture: "Is there any reason for every person who desires this knowledge not to have access to it?" We can now ask ourselves, "Is it not to the advantage to all citizens, in our struggle with entropy, to build a deep soil future - a deeper rooted commerce based on regenerative agriculture?"

The knowledge associated with increasing regenerative production at the base of Mirabeau's tree is economic development through environmental management, but also through building social resilience. This study does not provide policy analysis, or social prescriptions, but focused instead on a framework for adaptive management to provide a generalized approach and method for environmental feedback and developing stories that provide guidance for policy making and management. Because the contemporary social and funding mechanisms are still largely in the conservative conservation "K" phase of the adaptive cycle (Figure 11), while technology is in the reorganization "Ω" and growth "r" phase, funding and institutional structures built upon the status quo do not yet support the action outlined within this study. However, the cases and open source examples, which are at the growth phase of the adaptive cycle, provide approaches to systems change that can interact with the existing structures, continue to be applied and refined, and ease the transition of the social structures from the conservation phase through release and reorganization phases. This process can be continued and refined while also learning by doing, by prodding the system, and building networked learning communities during transitions. The remainder of this chapter will also follow the dissertation structure by summarizing each of the first three parts, followed by broad conclusions and next steps.

The emergent open source social, technical and biological systems and the intersections with radically reduced cost of tools to observe, access, and communicate knowledge that make collaborative adaptive management possible. The low-cost nature of the emerging digital based systems enable replication and more iteration. The number of calculations, data collection points and iterations, accelerate the evolutionary process to create reliable and reproducible building blocks for those systems create the potential for greater simplicity rather than complexity. As Kelly (2010) observed, we are consciously or unconsciously creating a singular machine of great redundancy. The Internet has run continuously for a little over 5000 days, and by 2007 already equaled the complexity of the human brain, however the human brain doesn't double every two years, and that difference is crucial in examining the future of adaptive management. These factors are beginning to converge to meet the criteria of required for simplicity and the transition from specialized technology to inexpensive, reliable, modular and reproducible tools.

The historic difficulty and complexity of systems observations had previously led to oversimplifications of systems descriptions. Those conditions are clearly changing with the evolution and simplification of the basic data gathering and dissemination building blocks, and with that comes changes in what can be measured, who asks what questions, how those questions are funded, and who has access to the resulting knowledge. The change in cost and resulting simplification of complex processes has already changed the economies of scale that were important factors driving large industrial and social scales that were required for efficient industrial extraction and colonization. The technology to monitor human changes to the biosphere is no longer a barrier. This change also shifts the burden to the social systems, rather than the technical systems, to make meaning of the technological changes and then apply them productively to the agro-ecological systems that will provide further positive economic, social and technical feedbacks. By creating a structural relationship that links the economic, social, technical and biological systems, this study provides a useful framework and historic context to identify methods for interdisciplinary adaptive management, and next steps to reduce external costs through transparency and access to knowledge.

Biological - Promising Field Trials and Research Methods

Challenges to interdisciplinary systems analysis are especially strong in agriculture just because so many systems and disciplines intersect and are embodied in the practice of agriculture. Organic systems, in particular, tend to be more biologically complex because they rely on the enhancement of ecosystem function rather than inputs to prosper, and therefore it is more challenging to quantify and study the variables independently. This approach requires the use of systems indicators when precise mechanisms cannot be identified, and an inductive, exploratory approach as discussed in Chapter 6. The complexity of collecting vast amounts of data in the field has historically added to the cost of data collection.

As processing power, observational technology, and data storage costs have vastly reduced, the cost associated with complexity has also been reduced. The decoding and open sourcing of the human genome, provides a template for this next stage of work and biological understanding. The implications for biological understanding are alluded to in this study, but early examples of applications of these new systems would be to test all possible interactions and combinations across the cover crop periodic table, illustrated in Figure 61, using a distributed Agricultural Knowledge Systems structure as outlined in Part II of this study. Some examples of exploratory on-farm trials already underway include incorporating multispecies diversity studies with:

- Reduced tillage trials (strip tillage, zone till, undercutting)
- Organic covercrop termination methods and suppressing (solarizing, undercutting, scalping, overgrazing)
- Pasture cropping – and introduction of warm and cool season species at different times and structure diversity and combinations, and levels of stress.
- Stacking functions across animal, fungal, bacterial and plant systems.
- Cover crop succession management across different times, structure diversity and combinations, and levels of stress.
- No-till establishment of annual covercrops into perennial grass legume sod at different times and structure diversity and combinations, and levels of stress.

- No-till establishment of warm season annuals into winter annuals with mechanical termination by crimping.

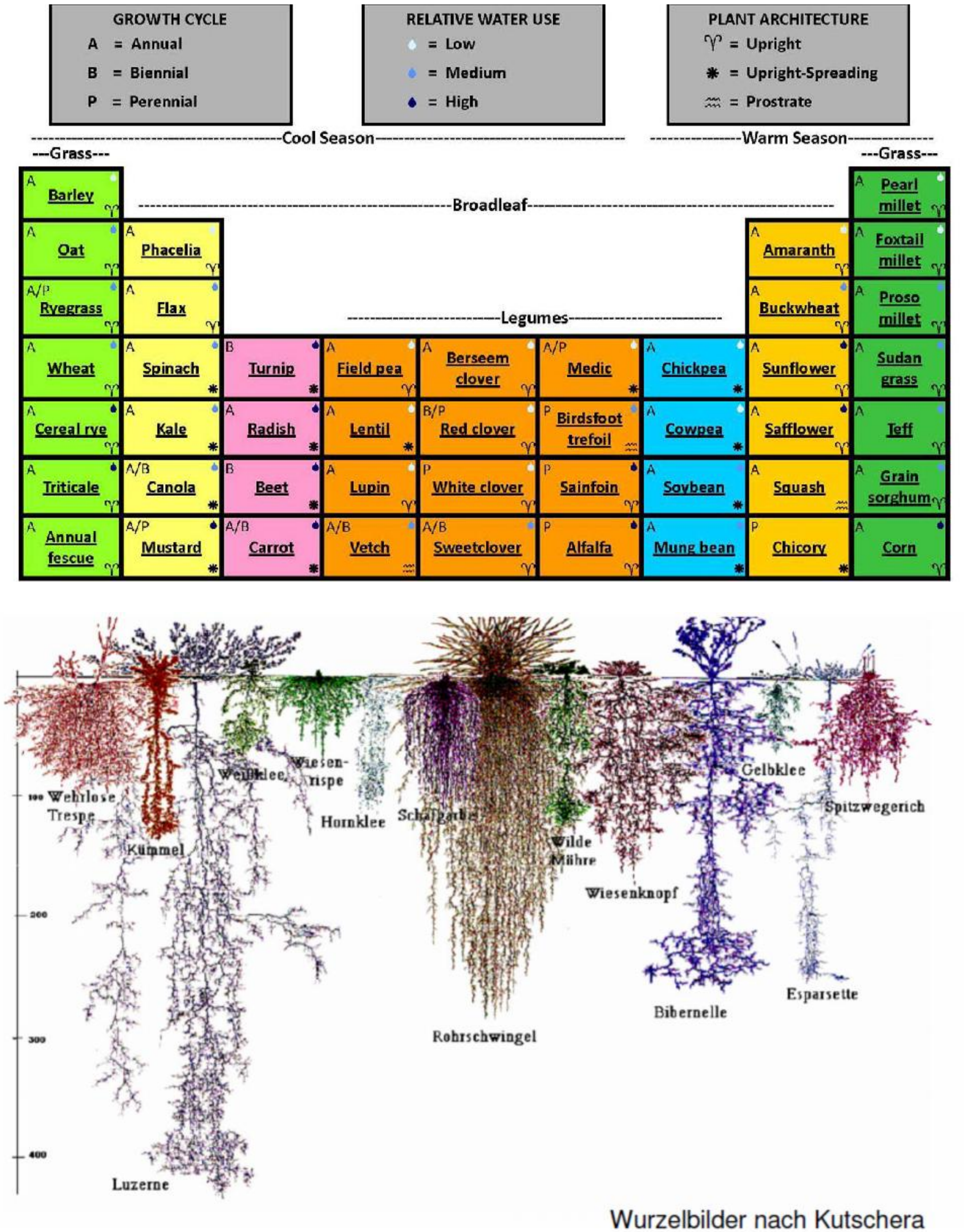


Figure 61 – Multispecies interaction mapping and documentation. Detailed imagery, and structural mapping and documentation of multispecies interactions form the basis for future inductive research. Imaging and remote sensing above and below ground could play a role in managing the complexity of recording observational data and identifying patterns of behavior. The figure illustrates a baseline approach to categorizing above and below

ground characteristics for testing. Adapted from the ARS Cover Crop Periodic Table ("Cover Crop 'Periodic' Table, Soilhealth.net" 2014) **and** (S. Braun 2012).

Observational technology, when coupled with an appropriate social system, could be used to expand the basic cover crop periodic table from a generalized static table to a dynamic, inductive research tool (a computer-aided Baconian table) that would also include below ground soil root interactions, nutrient flow mapping, and animal-plant-microbe combinations at the field and watershed level. Biological understanding will also require testing tools and their interaction with the above and below ground plant-soil interactions across the periodic table and observing and recording combinations of applications at different depths and frequencies. Inductive methods coupled with deductive experiments and low cost modeling can be used to identify patterns and develop and test new theories faster.

Technical challenges – in search of simplicity

Chapter 1 outlined a desired state for observational technology. It stated that technology should be accessible, ubiquitous, accurate, and low cost. In essence, the process to achieve those goals parallels evolutionary pathways that built on low energy, efficient cellular structures to produce complex structures that reproduce accurately billions of times without error. As Antoine de Saint-Exupery famously said, "You know you've achieved perfection in design, not when you have nothing more to add, but when you have nothing more to take away" (Saint-Exupery 1939). Nature has excelled at that task, and bio-mimicry is the study of applying natural problem solving to man-made systems. The pathway to simplicity also mimics natural evolution from single cells to the evolution of eyes. The pattern is replicated in silicon form through the incremental building upon basic binary code to record logic with transistors into incremental structures that create complex but dependable processing power that forms the basis of the internet, and makes possible the powerful but simple evolutionary forms such as the internet search box.

The next incremental stage of this pathway to simplicity, is through the extension of linkages not just between computers, and data, but to the coming "Internet of Things" and hyperlinking data and meta-data generated by billions of ubiquitous sensors all over the globe. The move from linking machine to machine to linking data to data has already happened as expressed by protocols such as KML, RSS, APIs, RDF and OWL (Kelley, 2014) which is a step toward linking to the "Internet of Things". The ubiquity of these systems is arriving at a pace faster than we are able to culturally assimilate the implications. The complexity of the system is made possible by the simplicity and most basic nature of the mechanisms, and the same process can be used to create improved and "simple" understanding of biological systems as discussed in Part III. The processes and workflows identified in Part III clearly require additional investigation and work to improve and make accessible, and move from the complex and specialized to the simple and accessible. Some categories for future work include improvements of management tools, data collection platforms, calibration of sensors, and post processing.

Management visualization and decision support modeling

FarmOS emerged as a project out of iFARM and was profiled in Chapter 6. FarmOS is also based on the development of standards that enable data collection, and sharing data where it is through trusted relationships, rather than central repositories, and return analysis in context to provide greater value. The development of an easy-to-use system to collect and disseminate decision support and reporting functions is not a trivial task, but the process is made more manageable by using open source modules and approaches that have already been tested and refined in other fields. The network architecture exists to host data locally and create APIs that make it accessible based on qualified requests. Data privacy issues clearly remain, but this is a challenge not unique to agricultural management software and is currently being worked on by the broader open source community for other applications with the same issue as issues associated with other personal data. Social protocols for gathering and sharing data and building trust and fellowship are part of the process of developing the next processes.

In addition to trust and data security issues, the system is one that grows in complexity as people use it, and whose benefits become greater to the users as they use it. The first adaptors, like the first adopters of a fax machine, get greater incremental value as more people start using the same technology. This aspect of the technology, also creates a sort of evangelism in similar communities. As shared data gets tagged with meta-data it adds value to others work, the return on participation increases in value, and increases incentives for participation. This process is been illustrated in the form of Microsoft's Photosync technology.

Data Collection Platforms

In addition to improved and more accessible management software, the hardware and networked sensors, aerial platforms and cameras, although accessible in cost, are still very challenging and technical to set up to work well, and require substantial skills to troubleshoot, along with frequent reliance on community forums for technical support. The networking hardware has reached a stage where it is fairly mature and low cost; however, the software setup could be substantially improved to make integration and addition of additional nodes faster and easier. There is also substantial work in creating accurate and low cost sensors to take advantage of the networked data loggers. Many sensors included in smartphones have dropped in price, but many have yet to be tested to measure environmental conditions, and the development of weatherproof housings, standard power sources and connections remains to be done. There are also additional platforms to be tested in order to gather plot images in more varied conditions including pole-mounted or hand-held systems for smaller scale highly detailed analysis, depending on scale. With the expansion of the community exploring these approaches the technical knowledge base for networking and calibrating sensors also expands in the form of wikis and forums.

In addition to improvement of sensors themselves, there are clearly opportunities to develop field set-up protocols that will also reduce post-processing cost, time and expense. For example, calibration cards that also serve as geo-reference points and ground truthing points could be used as field markers at the beginning of the season, thus reducing layout time, and data collection costs as well.

In addition to the examples listed above that reference the current state of technology, the other constant is that the technology is also constantly changing. The dynamic nature of the technology and new types of sensors illustrate the need for a process that is also adaptive. For example, low cost LiDAR may substitute for structure from motion processing gathered from still images, although the general workflow of gathering texture and volume information and the process of data standards and exchange remains the same. The rapid pace of new technical developments enabling low cost observation technology, also highlights the opportunity for new sensor and imaging hardware integrations and developments. For example, soil probe mounted imaging, conductivity and electro magnetic resonance imaging is already being done by closed source systems, but has a great potential for very low cost systems using boroscopes and similar medical type hardware for analysis in-place and other non-destructive methods that include field processing protocols for root and soil imaging and analysis including nodule color analysis discussed in Chapter 6.

Calibration Set-up

Additional work is clearly needed to create rapid and automated processes for calibrating low cost sensors as they are developed. The longer term adaptive management process was described in Part I to validate indicators, however, where there are known calibrated devices available, and the process is calibration and not validation, the whole effort can be made much simpler. This has been accomplished in the open source UAV community to calibrate compasses by using redundant references of gyroscopes, and GPS data to check one another and use the deviations to make adjustments and improve calibration over time. The same basic approach could be applied to ground based and aerial sensors. Environmental models will also benefit from calibration processes. The processes to manage multiple types of data is not yet well integrated into many of the programs, and to get data into a usable form often requires several steps.

Post Processing

The social objectives of the post processing workflows are to create low barriers to entry so that more complete data and meta data from imagery and sensors is entered by a greater number of participants. In their current state, there is a tremendous amount of work to improve the accessibility of post processing software and associated post processing image analysis and modeling workflows. The closed source software packages such as Pix4D and AgiSoft perform limited functions fairly well, but do not enable expansion or flexibility in use. Open source products identified in Figure 43, such as Visual Structure From Motion, Ecosynth, Meshlab, and environmental models like DNDC are accessible to an academic audience, but are not refined enough yet for general use. In the near term, it seems unlikely that end users such as individual farmers will use image analysis software directly, but instead will be able to access the processed images through service providers and agencies like the USDA/NRCS. However, as automated object recognition and other complex interpretation models improve, the amount of data that can be fed directly back without interpretation will also increase.

Post data processing of large data sets also opens up the potential for linkages with public health models and pathogen tracking which could tie in with soil management practices linked to air and water quality. The more stakeholders and users of land management data there are, the more crucial are trust and data privacy issues; as has been discussed throughout this study, more engaged stakeholders necessitate a more adaptive and collaborative research model.

Recommendations and Reflection

It is appropriate to end the interdisciplinary work of this study with a broad reflection on the cultural aspects of this work. It is through cultural interactions that we synthesize knowledge, interact with technological tools, and communicate biological systems understanding. The case studies in this dissertation illustrate that the limiting factor in improved environmental management is cultural rather than biological understanding or technical capacity. The call for "innovative innovation" highlights the need for a shift in the governance of agricultural research and innovation in order to achieve a resilient future.

In order to make progress in sustainable agriculture, new methods and approaches will be required. Some of the key elements of the collaborative adaptive management framework called for include:

1. Immediate management feedback indicators (water, nutrients, crops) that are easily communicated and translated into management actions.
2. Rankings and ratings to compare decision making and performance with others in the community, watershed and beyond to create social perception of stewardship and self-evaluation.
3. Easy-to-use tools that reduce recordkeeping, reduce reporting requirements for certifications and compliance, and also improve feedback and free time for strategic thinking.

4. Creation of communities of practice that enable new data driven markets and incentives that could include prizes, equity value in land, environmental service payments and social recognition for measured performance.

5. Creation of a system that values participation and protects the value of the data, and promotes monitoring and sharing data as best management practice.

Despite technological achievements in environmental observation technology, the result will not *necessarily* be a more sustainable society, i.e., a society that is characterized by a better balance between economic, social, and ecological goals. The newly available observational, analytic and communications technologies have yet to be culturally assimilated. Unlike the re-combination of existing technology, cultural change is an incremental process. However, just as with biology and technology, complex systems can be made simpler through greater understanding and building upon reliable, inexpensive, and replicable functional units.

The cultural aspects and intersection of technology and human values is a major challenge for agro-food systems that calls into question the relations between agronomic sciences, agricultural technologies and public and private expectations for science, participation, and citizenship. The Physiocratic framework embodied by Mirabeau's Tree provides an accessible metaphor that gives cultural value and import to open source agricultural research and development methods. Advances in technology will continue, but how they are applied, who controls them, and the knowledge collected has profound implications for our future. For this reason, a whole systems approach is crucial to provide not just a technical framework, but a social and Physiocratic open source approach to collaborative adaptive management.

Internalization

The open and networked framework explored within this study provides a hopeful approach, as the process does not necessarily need to be fully understood to be managed. New, networked internet tools have made it possible not to need an organization to be organized, as illustrated by the open source community projects profiled. The cases chosen for this study illustrate that with proper platforms, content can be almost entirely user generated; in fact, that self-organizing collaboration, volunteer efforts, analysis and internalization of values is possible.

The technology explored within this study was expressed in terms of technical tools for observation, but also within the cultural practices expressed as collaborative software, and documents and documentation of open source organizations as products of their social practices. Through these methods the inventor will most likely not be the one who will know what the ultimate use may be, and the ultimate use will be collaborative and emergent. A substantial portion of the innovation will come from people who work at their leisure and create communities of innovation around their passions, and are more likely to put their work back into the creative commons. This process is a continuation of the process of cumulative printed knowledge that started with printing press, and is leading to networked intelligence, that can be drawn upon by all. Beyond sharing information and knowledge, the cumulative process of sharing and refining environmental observations and models begins the process of shared intelligence. The by-product of the first 5000 days of this process is already an immensely rich virtual model of every part of the Earth, collected not just from overhead flights and from satellite images, but from networked sensors and recorded observations in what is becoming a collective memory.

The coordination across open source communities, documentation and trust through transparency is a crucial aspect for understanding social systems and how they react when under pressure. Empowerment within this new system is an issue that will also require further study. In a highly networked system, there is the potential for a leadership vacuum, and yet through bio-mimicry we can see examples in nature of vast flocks of birds that are able to navigate without collision and change course in coordination, and so a vast effort is possible, through means we are only just beginning to understand. The Physiocratic framework for adaptive management provides a working model to structure further exploration.

"whoever could make two ears of corn or two blades of grass to grow upon a spot of ground where only one grew before, would deserve better of mankind and do more essential service to his country than the whole race of politicians put together" (Swift 1726).

Appendix

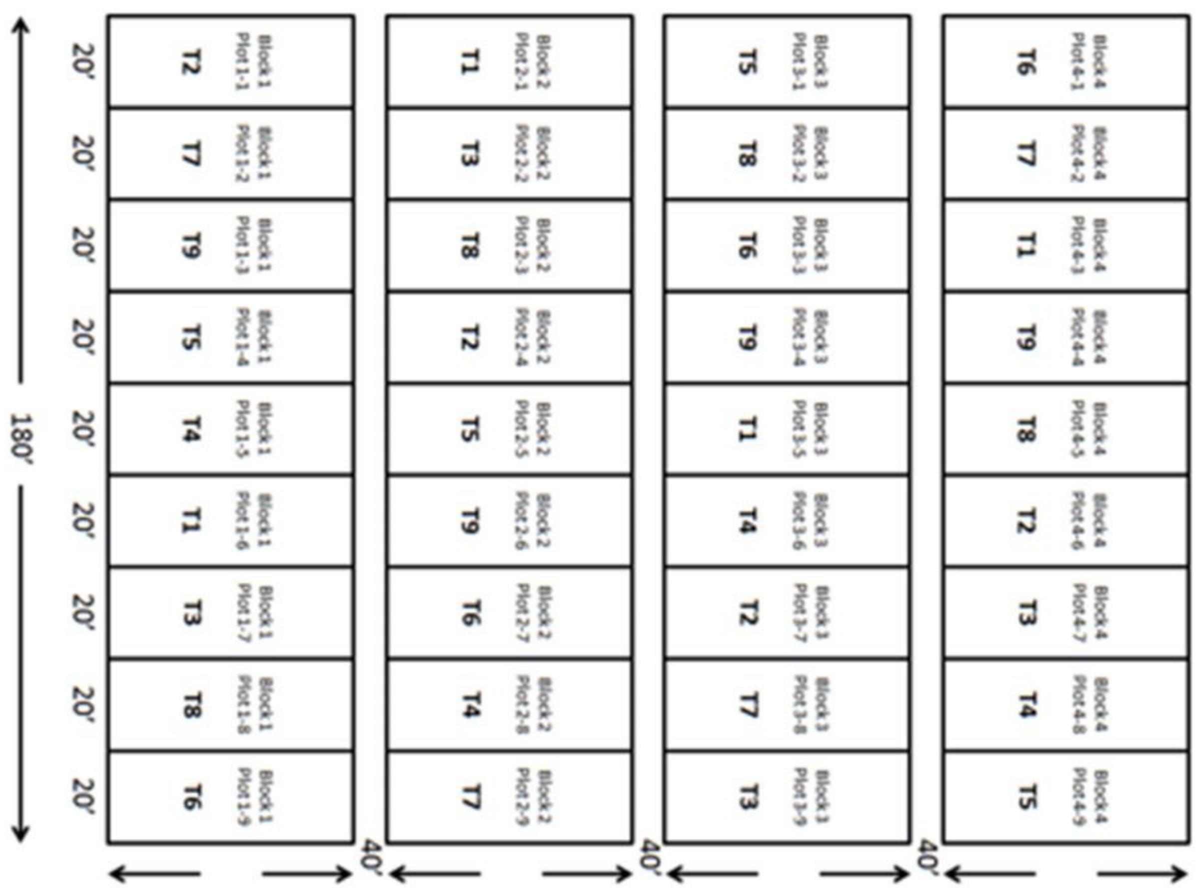
Field Experiment Ground Truthing Background for Hairy Vetch plots

Field experiments were established in 2011 at a hay meadow located in Lee, New Hampshire. The hay meadow was under no-till management prior to and for the duration of the study. The plant community of the meadow was dominated by orchard grass (*Dactylis glomerata L*.), timothy (*Phleum pratense L.*), sweet vernalgrass (*Anthoxanthum odoratum L.),* buttercup, (*Ranunculus spp.),* and hairy vetch. The soil at the site is a Buxton silt loam (fine, illitic, frigid Aquic Dystric Eutrudepts, USDA) and organic matter content ranged from 6.6 to 8.6 %. The vegetation at the site was harvested as hay in July each of the five years prior to the study.

The underlying agricultural field trial's objective was to identify amendments that significantly affect the biological competitiveness of no-till hairy vetch when planted into perennial hay sod in degraded hayfield conditions. Of fourteen treatments and four replications in a randomized complete block experiment, there were three wood ash treatments (four, six, and eight tons per acre) that yielded the only significant improvement in organic no-tilled vetch biomass. The trial was designed to isolate which effect of the woodash was most important in increasing vetch competitiveness. The primary effects being tested were pH, potassium, or carbon. The range of wood ash treatments was also tested to identify the level of diminishing returns. The carbon effect was tested with bio char and hardwood shaving treatments. Lime and potassium treatments were tested with both lime and fast-acting lime as well as mineral KCL.

Field experiment Ground Truthing Background for Corn Plots

The field based portion of the experiment was based on the 2013 field trial titled *Grain-alfalfa intercrop field experiment* created and managed by Dr. Richard Smith and his agro-ecology lab at UNH to explore organic reduced tillage methods and alfalfa crop rotations on long term soil health and grain corn production.



The treatment details are as follows:	
T1: Full-tillage + inter-row cultivation Moldboard plow, plant corn, 2-3 inter-row cultivations post corn emergence **T2: Full tillage + inter-row cultivation + legume inter-seeded at final cultivation**	**T5: Undercut (Yeoman's plow with undercut knives)** Mow or flail chop alfalfa very close, undercut with Yeoman's plow, plant corn **T6: No-till + glyphosate burn-down**

Moldboard plow, plant corn, 2-3 inter-row cultivations post corn emergence, inter-seed with crimson clover at final cultivation (at corn V4-V8 stage) **T3: Strip-tillage** Mow or flail chop alfalfa very close, strip-till, plant corn **T4: Strip-tillage + glyphosate burn-down** Stress or kill alfalfa with a burn-down application of glyphosate, strip-till, plant corn	Stress or kill alfalfa with a burn-down application of glyphosate, no-till plant corn **T7: No-till + glyphosate burn-down + legume inter-seeded** Stress or kill alfalfa with a burn-down application of glyphosate, no-till plant corn, inter seed crimson clover at corn V4-V8 stage **T8: No-till + flail-mowed alfalfa** Mow or flail chop alfalfa very close, no-till plant corn **T9: Alfalfa** Manage as alfalfa hay

Soil samples were collected from each plot for the Cornell Soil Health Test at the site where baseline plant community biomass was harvested from three randomly placed quadrats per plot (0.25 m). On June 17, 2014 manure was applied to all the plots at approximately 50 lbs N/acre. The "burn-down treatments" had recommended rates of Glyphosate applied on June 20, 2013 and "mowed" treatments were flail-chopped. Tillage treatments were established using conventional moldboard, strip-till, Yeomans plows. One June 21, 2013 moldboard treatments were disk harrowed and non GMO, 82 day Corn was planted across all treatments (except T9). Weed biomass was collected in August 2013, grain moisture, and soil moisture readings, test weight and grain yield were collected in November 2013 with a Kincaid x8 Plot Combine.

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