# Computational Agroecology: Sustainable Food Ecosystem Design

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## Abstract

We propose a new domain for sociotechnical system design: creating new ecosystems for food production that are sustainable while producing high yields. Drawing on the field of agroecology, we discuss techniques for allowing a range of users to design sustainable food ecosystems that can overcome the environmental costs of industrial agriculture. Industrial agriculture, relying on declining reserves of fossil fuels and generating increasingly costly externalities, is unsustainable. Agroecology cannot scale until practitioners have access to detailed knowledge of local conditions and appropriate agricultural strategies. This paper reviews the agricultural and sustainability challenges that motivate our research. It describes design problems that must be addressed to scale agroecology. We discuss our initial work, and sketch a program of research we believe will contribute to global food security.

## Author Keywords

Sustainable HCI; Agroecology

## ACM Classification Keywords

H.5.m [Information interfaces and presentation (e.g., HCI)]: Miscellaneous

## Introduction

A small but important stream of research in HCI has pointed to food security as a common concern. Around the time sustainable HCI began ramping up, HCI research in "food futures" also began (see [6, 10]). A challenge of sustainable HCI has been the identification of relevant problems and domains for research [41]. Formulating sustainability research questions is hard because the problems can seem overwhelmingly global and large-scale. Research often succumbs to greenwashing, and small, clever, but unimpactful responses. While the problems of the global food system are large-scale and can indeed be overwhelming, we describe what we believe is a tractable approach for research to improve global food security.

We discuss our vision for sustainable global food systems through what we call *computational agroecology*. We are only beginning to develop this subfield, and have initiated projects that we are currently expanding [30, 31, 43, 44]. Through this paper we hope to engage other researchers, learn about relevant research that we might not yet have encountered, and discuss the problems of food security as we see them. Ongoing HCI design efforts such as *Nutrire Milano: Energie per Cambiamento* (Feeding Milan: Energies for Change) [5], civic agriculture [25, 42], urban agriculture [22, 33, 34], hyperculture [18], neighborhood food sanctuaries [21], and even support for practices such as "scrumping," [48], can inform, and be informed by, computational agroecology.

The premise of our work is that industrial agriculture, which has been central to contemporary civilization, is fundamentally unsustainable. Its dependence on non-renewable resources (fossil fuels for chemical fertilizers and pesticides, fertile topsoil, abundant clean water) and its massive, destructive ecosystem effects (erosion, oceanic dead zones, greenhouse gas emissions) indicate a critical need to switch to new modes of food production [2, 18, 19, 24, 46]. It is estimated that up to 29% of all greenhouse gases emitted globally are due to the industrial food system [47]—the largest among all sectors of human activity—by itself a reason to turn to new means of food production.

Over the last few decades, scientists in the field of agroecology have identified approaches to reconcile human food needs with the broader planetary ecosystem and its limits. Agroecology is "a scientific discipline that uses ecological theory to study, design, manage and evaluate agricultural systems that are productive but also resource conserving" [1]. The key to agroecology is the design of fully-functional and sustainable ecosystems of food crops, modeled on nature.

Despite the potential of agroecology, industrial agriculture continues to dominate. Its brute force approach deploys easily replicated, generic techniques such as monocultures of annual crops managed with fossil fuel-derived fertilizers, pesticides, and herbicides. It is only since World War II that such practices have appeared, diffused by intense government efforts and spurred by the decision to re-purpose explosives factories (which turned to making fertilizer after the war) [46]. This unsustainable approach has not been made accountable for the depletion of non-renewable resources and the severe environmental damage it causes [14], as these impacts have been ignored as economic "externalities".

With respect to HCI, agriculture in general and agroecology in particular are unique in that they are universal in their potential reach: virtually all humans today are dependent upon agriculture for their sustenance. Transforming agriculture can directly impact and engage people in myriad roles in the context of food production. We thus propose a

**Figure 1:** A polyculture in a community garden in Urbana, IL. (Photo credit: Sarah Lovell.)

new domain of research, *computational agroecology*, which aims to *scale* agroecology, including making the techniques accessible to a wide range of users. Potential users include farmers, scientists, students, educators, civic leaders, policymakers, and any member of the public who wishes to have a role in sustainable food production. The three core technical sub-areas of computational agroecology that we explore in this paper are 1) systematization and modeling of agroecological data, which will require the harnessing of human expertise via crowdsourcing, 2) the interactive design of agroecosystems, which will require careful attention to the context and to user needs, and 3) systems, including robotics, for maintenance, harvesting, and integration of agroecosystems that leverage and balance the best of human and machine abilities.

Computational agroecology will enable the transformation of many types of land to new food-producing ecosystems consonant with the specific conditions of local regions, and consistent with long-term ecological health and food security. Some of this land is already farmed or gardened, but, in addition, unused capacity in backyards, rooftops, parks, campuses, and other civic spaces can be brought under cultivation. The urban agriculture movement is already seeking to transform urban practices. When applied with deep knowledge, agroecology can be used in a wide range of settings, from smallholder farms to large tracts, urban gardens to untended semi-wild lands, all transformed to productive, sustainable food-producing ecosystems.

## Agroecology

Any sustainable alternative form of food production must 1) greatly reduce the use of non-renewable resources and production of non-assimilable wastes, 2) reduce the need for external renewable inputs, and 3) adopt techniques that regenerate rather than harm the supportive ecosystem services that enable long-term agroecosystem sustainability.

Agroecology is a transdisciplinary science, and as a result, it is quite complex and difficult to summarize succinctly. To give a sense of its scope and "spirit," next we describe several techniques that are often employed in agroecological design. These are only examples from a much larger body of scientific work, work that includes research on the broader food system, including food distribution, waste, political and economic impacts, and more [2, 19, 24, 46].

Agroecological systems can produce yields greater than industrial agriculture without the harmful side effects [19, 37], though traditionally they also require more labor. A polycul-

**Figure 2:** A perennial polyculture farm in Pahoa, HI growing several hundred varieties of fruits, nuts, and vegetables. (Photo credit: Barath Raghavan.)

**Figure 3:** Perennial herbs attract pollinators to the Good Cheer Food Bank Garden serving the homeless in Seattle, WA. (Photo credit: Anh Bui.)

ture is a multi-species group of plants that live together and, often, support one another. One of the best studied simple polycultures is the traditional corn-bean-squash intercrop system from the Americas. This system can not only double the effective yield of industrial monocultures, but offers "[n]et gains of nitrogen in the soil...observed when the crops are associated" (i.e., the polyculture increases soil fertility without external inputs) [19]. Polycultures can be considerably more complex than this simple 3-crop system; Figure 1 shows a moderately-complex polyculture.

A common feature of agroecological systems is the use of perennial polycultures [13, 26, 35, 36, 40]. Perennial polycultures involve plants that live for more than two years or self-seed annually. Constituents in a perennial polyculture provide support services to each other and require few external inputs. Well-designed perennial polycultures provide products and services for human use over the long term. Due to their longevity, perennial polycultures minimize ecosystem disturbance, preventing topsoil and nutrient loss, such as the farm shown in Figure 2 and the garden shown in Figure 3. They promote ecosystem diversity, increasing food security. And they naturally trap available resources due to deeper root systems, taking advantage of the soil's water storage capacity. Perennial polycultures are a common feature of many agroecological design methodologies and were the basis of traditional agriculture in some regions of the world.

Another common feature in agroecological systems is the leveraging of natural flows of resources including water, sun, nutrients, and beneficial insects, such as in Figure 3. A key process here is ecological succession, in which pioneer species (the first species in a multi-year succession) help restore an environment and enable the growth of more durable species that will overtake them [11].

## Background: Agriculture Past and Present

Why is agroecology needed? What about organic agriculture? Shouldn't that solve the problems with industrial agriculture? How about bioengineering? These approaches and others have value, but they do not go deep enough to address the core problems.

### *Organic Agriculture*

Over the past two decades, organic agriculture has risen from a niche to an alternative providing consumers in many markets easy access to organic produce. Organic agriculture seeks to produce "products using methods that preserve the environment" [45]. This development has been a welcome change. However, while organic agriculture aims to have improved ecosystem impacts, it is still locked into many of the same practices as industrial agriculture, including, most notably, monoculture and reliance on fossil fuels. Organic agriculture is an important step away from the industrial system, but is far short of what is needed [39].

### *Companion Planting*

For millennia, human civilizations have engaged in the process of companion planting, i.e., cultivating multiple species in close proximity to each other for mutual benefit. Scientists have confirmed the benefits of such strategies [28]. However, companion planting has typically been constrained to a small number of species, due to the combinatorics of the problem and the lack of data to support more complex designs. We are at a unique point in history when a much greater amount of data on plant species is now globally available (albeit sometimes scattered and inconsistent), and when we have the algorithms and computational power to begin to address the problem at a larger scale.

### *Bioengineering*

Over the last few decades, crop bioengineering has become commonplace and central to industrial agriculture in many regions of the world. Often crops are bioengineered to resist pests, withstand harsh conditions, or take on some other trait that is not found in that crop species (and thus cannot be bred in through conventional breeding). Some systems of alternative agriculture, like organic agriculture, explicitly forbid bioengineered crops. Bioengineered crops can be successful in some settings by producing greater yields or pest resistance, and they can also be failures in other settings by promoting unforeseen pest resistance and annual monoculture plantings. Bioengineering is orthogonal to agroecology and is not required for the success of agroecological design.

### *Other approaches*

There are a number of other interesting alternative agricultural methodologies that are being practiced today, including research into perennial grain crops [12, 20], aquaponics, biodynamics, and permaculture [27]. For brevity we do not describe them in detail here, but note that each methodology contains some useful insights into the design of agroecosystems, while not providing the scientific rigor and breadth of agroecology [15].

### *Industrial Agriculture*

Industrial agricultural systems have shown both their potential and their pitfalls over the past 70 years. These highly-mechanized (and data-driven) crop systems, now leveraging bioengineering and chemical responses to pests and pathogens, have yielded vast quantities of food with minimal labor. However, in doing so, industrial agriculture has denuded the land in some of the formerly most fertile growing regions of the world, locked the food system into a dependency on fossil fuels, politicized scarce resources (such as water), and created a cycle of escalation in combating crop threats due to pest and pathogen evolution [19, 46].

Industrial farms are typically monocultures, i.e., fields planted with a single plant variety, something that rarely occurs in nature. Monocultures form a precarious base from which to ensure food security: they can be wiped out by a single pest or pathogen, a single bad weather event or climate disturbance. Limits to this industrial paradigm are imminent. Of greatest concern is the declining availability of key non-renewable inputs, i.e., fossil fuels to produce fertilizer and pesticides and to run farm machinery; topsoil in major growing regions; and groundwater deposited at the end of the last ice age. These “hard” limits have the potential to decrease yields: 80% of IPCC climate projections show crop yield decreases by the end of the century, which in some scenarios may exceed 50% [23], while billions more people are added to the global population.

The intensifying effects of “soft” limits such as water scarcity, soil fertility, pollution from pesticides and fertilizer runoff, and the extreme conditions produced by climate change exacerbate the problems. Industrial agriculture has only been “efficient” if we ignore its hidden subsidies of non-renewable rich soils, fossil water, and fossil fuels, as well as government subsidies in the US and Europe, and if we ignore the immense wastes industrial agriculture generates [38]. The system depends on extractive activities that consume natural resources that are not replaced within the cycles of food production. For example, in California, rice grown in the Sacramento Valley is organized around aviation: "Flying at 100 mph, planes plant the fields from the air" [9]. In addition to the fossil fuel for flying, rice requires enormous infusions of water in a region of low precipitation. All of this, and yet rice production in California provides few jobs and most of the rice is exported, in effect exporting water [16]. Such a mode of production generates wealth for the few, using scarce public resources for profit-driven enterprises that do not distribute wealth through employment or by feeding the populace.

## Computational Agroecology

Why are computational solutions needed? As Odom’s study participant famously said, "Mate, we don’t need a chip to tell us the soil’s dry" [32]. We agree. So what is it we don’t know about agriculture, which humans have been practicing for millennia? We argue that agroecology is a fundamental shift in thinking—it is intended to to create *ecosystems* not just farms and gardens, that exhibit biodiversity comparable to natural systems, and that become as high yielding and self-sustaining as possible. We have many more people to feed in the world today than ever before, and we have the complexities of climate change and a declining base of natural resources to deal with. In addition, some traditional agroecological knowledge has been lost [3].

In order to create such ecosystems, agroecological practitioners must have at their fingertips detailed knowledge. This knowledge includes local biogeochemical conditions; climatology; numerous plant, animal, and insect species; land topography; soil ecology and chemistry; agroforestry; water management; inter- and intra-specific plant competition; terraforming; species sunlight requirements; and plant propagation. Practitioners typically need decades of hands-on experience to translate this knowledge into functional agroecological systems within specific contexts. Relying on individuals to accumulate and apply this necessary knowledge is a major bottleneck; Norton points out that few experts exist and too few new experts are being trained [29]. In addition, while the scientific knowledge of agroecology is well developed, it is largely inaccessible to those outside the scientific community. Local, informal knowledge, which can be very valuable, is scattered, inconsistent, uncontextualized, and non-systematic. Techniques of agroecology can be adapted to many thousands of ecologically-unique sites of food production, but doing so requires the information necessary to build complex, productive ecosystems in each setting. It is here that we believe there is a key role for human-computer interaction: the design work, the subsequent implementation and maintenance of food producing units, and the education of new experts, can be greatly aided through the use of computational tools.

We view computational agroecology as the design of computing systems to aid in planning, building, and maintaining sustainable agroecosystems. These computing systems need not be a permanent presence; they can be self-obviating [43]. A first step is to begin building basic models to underpin interactive tools. Working with agroecologists (one of whom is a co-author of this paper), we need to build models of plants and their interactions with other plants, climate models for specific locations, soil models, and other pertinent models. These models will utilize information that is already known in existing databases such as, for example, topography from satellite data, soil surveys from the USDA, weather/climate models from NOAA, hardiness zone models from USDA, and wildlife corridors from EPA. Other information, scattered in forums, small informal databases, the minds of practitioners, and other sources, can be crowdsourced, which we discuss below as the first class of computational systems we envision.

These models could then be used in three types of systems for end users. The first user-facing system would aid in agroecosystem planning, producing designs for agroecosystems in a particular location for a user's specific objectives. The second type of system would help during implementation of a design on the land, and could include mobile or robotic tools to help with various tasks, e.g., robotics to help the user perform an accurate survey of the topography and soil conditions of their land. A third type of system would help in maintenance and harvesting in the food producing unit. For example, a robot could identify (and possibly pull) weeds. Other types of systems will undoubtedly be needed, but these three form the beginning of our research.

### *Crowdsourcing Agroecological Data*

Detailed knowledge about agroecosystems to inform the models and tools must come from the scientists and farmers who have spent decades studying the intricate relationships inherent in complex living systems. Using this knowledge to build models that can form the basis for end user tools can be approached as a problem of crowdsourcing. Significant agroecological expertise and data have yet to be formalized, residing in the minds and production units of scientists, farmers, practitioners of traditional agriculture, and the like. We need to extract this knowledge in a systematic way to build unified representations of the behavior of elements of agroecosystems. Knowledge extraction may take many forms: experts might be interactively surveyed on certain topics (e.g., complementary plant species), or they might directly enter data they know into a system. We can also data mine content from online gardening forums and YouTube videos. There are thousands of such forums and videos on everything from growing bananas in northern climates to precise methods for grafting specific trees [4]. Practitioners have years of experience that cannot be duplicated in any other way. However, the information needs to be brought into sophisticated models that can produce whole new sustainable ecosystems, not just used as one-offs, to say, grow bananas in Ohio. Scientific knowledge in agroecology is growing rapidly. For all but scientists themselves, this knowledge is difficult to access and interpret, so much of its value will be in informing the dynamics of the models. Crowdsourcing is well suited to be used with both scientific and informal knowledge. The crowdsourced data can be housed in a software infrastructure in which we can implement representations of the various phenomena in the data, and model the dynamics of the interactions among the various parts.

### *Interactive Agroecological Design*

Next we require systems that can help the user create a design for a desired agroecosystem. We do not expect that a fully automated system can design an agroecosystem; there are too many unknowns that are difficult to specify. The process of design must be one of guided co-creation between the user and the computational tools. By virtue of the inherent complexity of nature and the ongoing discoveries in agroecology, the models will never be complete. However, the aim is not to model an agroecological system for its own sake, but in the service of agroecological design. Imperfect but useful models can inform good designs. The key is for the models to capture meaningful characteristics of agroecological systems while allowing for continual refinement. We envision that people will be able to discuss designs in online communities and in peer interactions, critically examining the suggested designs, and taking advantage of knowledge and experience beyond the immediate users. For example, in some regions, certain crops may be desired over others, certain types of terraforming may be preferred or disallowed, certain species may be unavailable for propagation, or a region might be experiencing a multi-year drought or flooding.

The system must be able to evaluate the myriad possible agroecosystem designs and select one or a few that meet the user's objectives. Even simplified sub-problems of this selection task are likely computationally intractable (i.e., NP-Hard), as the process of choosing a subset of elements for placement (e.g., tree plantings) from all possible elements and locations (even ignoring interactions and context-specific details) quickly results in combinatorial explosion. As a result, finding an "optimal" solution is unlikely. The system must be refined in consultation with experts so that the designs it generates will perform well when implemented on the land.

### *Implementing Agroecological Designs*

Once the user settles on a design specifying the plants, their locations, and a plan for plant succession (and many other details), we must develop systems that can provide guidance as to how to physically realize the design on a specific piece of land. Agroecological designs often involve complex layering of species and earthworks over time and across space. For example, a design for digging deep earthworks must take into account the soil and the machinery required. Certain aspects of the design may need to be implemented first (e.g., swales to capture rainfall might be the first thing the user must dig), and the system must make this clear. Overall, the system should take an agroecological design, which has significant complexity over time and space, and turn it into something that can answer the following questions: What do I need? and, What do I do next? We envision that some mobile systems might be useful in this process, for example, a mobile system to guide the user on the land to ensure that swales are being dug along the land's contour lines.

### *Maintaining Agroecological Systems*

Agroecosystems, when well designed, can survive for hundreds of years. Friedman and Nathan [17] advocate multi-lifespan design, that is, design for systems that alter our infrastructures for long-term benefit. Agroecology is consistent with this approach—over a span of hundreds of years, it is possible to sustain a well-designed agroecosystem for productive use. Maintenance might involve something as simple as regular pruning of certain trees, or the gathering and scattering of seeds in certain locations at certain intervals. It might also involve repairing or healing unexpected damage, such as that following a powerful flood that uproots trees or destroys earthworks.

Harvesting is another aspect of maintenance. Due to the complexity of polycultures in which different crops are ready for harvest at different times, and are intercropped together in physical space, harvesting is more complex than in industrial monocultures. Human-robotic systems may be of value. It should be possible to design robots that can quickly identify crops that are ready for harvest, require pruning, or should be removed. Although robotic sensing, weeding, and harvesting [7], for example, exist for monocultures [8], research is needed to adapt the techniques for polycultures in which it is necessary to understand which plants are which, and where robotic navigation is more difficult because the characteristics of the plants vary. Robots powered with renewable energy might enable elderly or disabled users to participate to some degree in food production. An interesting technical challenge lies in how to develop technologies that engage a variety of participants at differing levels of physical robustness.

## Example Use Cases

While transforming the agricultural system is a massive undertaking, it can take place in concrete, small-scale ways, and be accomplished through the actions of many people in many places. In this paper we have proposed a technological approach to the adoption of agroecology, but that technology must be applied by key stakeholders for it to have real-world impact. Here we describe a few example use cases for the systems we envision.

Consider a user in need of an agroecological response to desertification. If she is a farmer, the system can help with 1) identification of potential water flows during the rare heavy downpours common in desert regions, 2) terraforming the land with earthworks to capture water and nutrients, 3) planting strong-rooted pioneer species appropriate to the climate and soil, and 4) planting food crops that leverage appropriate ecological succession for the local conditions. Even in this simple example, the farmer faces choices regarding where to build the earthworks, which species of pioneer plants and crops to plant, and how to configure them on the land. In a different case, a student using the system to understand desertification might not even have an interest in actual designs, but would use the system analytically to simulate long-term behavior in an ecosystem, so that he can study productivity and sustainability. A policymaker might want to step back from a single site or farm and understand the aggregate behavior of many neighboring agroecological systems.

Consider an experienced farmer who wishes to transform existing farmland (either barren or planted in an industrial monoculture) to a sustainable agroecosystem. The farmer would begin by telling the system her objectives. For example, she may wish to simply produce the highest sustainable yield possible with minimal effort required in maintenance and minimal cost in establishment. Or she may wish to specify that certain crops be grown, that the crops be easy to harvest, that no earthworks be required in certain areas of the land, and that the system be resilient to 1000-year floods. The farmer then describes the land to the system, both its location/extent and its current conditions. She would instruct the system on any known errors or gaps in the system's data. Some data might be insufficiently granular, e.g., satellite topographical information only includes large land features. To improve these data for himself and others, the farmer could walk the land using a mobile device-based tool to perform on-site surveys, gathering more accurate topographical information and data on the soil. On-site data would be fed back into the system to improve the quality of the model. Once the system produces a candidate design, the farmer may wish to add, remove, or modify certain elements. The system can provide feedback on these choices and alter other design components to ensure that the agroecosystem will be sustainable.

Consider users in the maintenance phase of work on their food-producing units. The system could enable, possibly through computer vision techniques applied to images taken by the user or by automated vehicles, the detection of when certain crops are ready for harvest. These determinations would not be based on pre-existing data or design assumptions, but based upon the on-the-ground conditions at the site. The user can then be notified of a potential harvest and can either manually harvest, or, if feasible and desirable, employ automated harvesters to harvest the crop. The same is true for maintenance, e.g., annual pruning of deciduous fruit trees, repair of earthworks, addition of new crops into the system, and so on.

## Conclusion

Today's industrial agriculture, reliant on non-renewable resources and causing continual damage to the global ecosystem, is unsustainable—that is, it cannot persist indefinitely [46]. However, none of the existing alternative agricultural systems is currently able to meet the challenge of feeding today's 7.4 billion people, much less the added billions that demographers project. We believe that we have an opportunity at this juncture to change the terms of the debate through the design of sociotechnical systems to implement sustainable new ecosystems for food production, allowing many kinds of users to participate in a variety of settings from backyards to civic and community spaces to sizeable farms. We believe it is possible to feed the world through systems that are more sustainable than current agricultural systems. Undoubtedly this goal will require many changes beyond what we have discussed in this paper, such as diets with less meat, greater efficiency in all parts of the food system, including distribution, shifts to more labor-intensive modes of production, restoration of degraded lands, and commitment to multi-lifespan design.

Some components of agroecosystems are naturally long-term, such as bringing trees to maturity, and breeding trees for greater yields and resilience. Yet it is also true that rapid change, at least in some areas, is possible. Just as Victory Gardens were cultivated as an immediate response to food rationing in the US during both World Wars, producing the equivalent of commercial production in fruits and vegetables during the war years, there is nothing stopping us from beginning to intensify and diversify our own food production efforts. We are further from agrarian knowledge than citizens of the 1940s, but we have access to unprecedented stores of information. The research we discuss in this paper on computational agroecology is meant to order, systematize, and make deep agroecological knowledge widely available and useful. Perhaps we live a moment in which we can both draw from the past and leap into the future.

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