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Agroecosystem Health, Agroecosystem Resilience, and Food Security

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Abstract— This paper lays out the relationships between three mutually reinforcing concepts associated with agroecosystems: 1.) agroecosystem health, the extent to which an agroecosystem can meet human needs for all of its residents over time; 2.) resilience, the capacity of a system to adapt, reorganize and maintain key functions in the face of turbulent and unpredictable change in its environment; 3.) food security, sufficient quantity and quality of food for everyone at all times. Agroecosystem health has been defined by a number of properties including: stability, sustainability, equitability, productivity, and autonomy, each in the context of specific spatial and temporal scales. Indicators that characterize biophysical and social conditions including soil health, biodiversity, topography, farm economics, land economics, and social organization can be combined using analytical hierarchy process to map agroecosystem health across a landscape. The resulting map may provide incentive and guidance for improving the conditions underlying agroecosystem health. Resilience and agroecosystem health overlap largely because both rely on diversity, in biological and physical as well as human cultural, social, and economic terms. The Agroecosystems Management Program at The Ohio State University has approached research and outreach to improve agroecosystem health, resilience, and food security by encouraging self-organizing social networks for economic development around local and regional agricultural

supply chains, encouraging farm enterprise diversity at a wider range of farming scales, and conducting research to monitor and estimate the benefits of such diversification. Social media tools have been explored for connecting entrepreneurs at the planning stage, with the ultimate goal of improving the economic support for more diversified enterprises in agroecosystems. Although challenging, such adaptive management experiments may create and encourage new opportunities for managing agroecosystem health, and with it resilient food production and security.

Keywords—Biodiversity, crop diversity, enterprise diversity, entrepreneurship, self-organization, sustainable agriculture

Introduction

In this paper I will first discuss a framework for agroecosystem health and then describe conceptually the role of healthy agroecosystems in sustainable and resilient food security. The goal is not to review the literature on these topics or present an evidence-based study, but rather to describe a conceptual model, a complex hypothesis, that is shaping research and outreach in the Agroecosystems Management Program (AMP) at The Ohio State University (OSU). The program began with a group of faculty who were willing to consider agriculture holistically. Rather than focusing on a list of production problems and solving them individually and sequentially, as is often the case in colleges of agriculture, we consider the entire list to be properties that emerge from agroecosystems, consisting of both people and the land interacting at landscape scales, for example entire watersheds. Our focus became what could be changed about the structure and function of the system as a whole so that new properties emerge, with simultaneous gains in social, economic and environmental considerations as the objective. That holistic thinking led to consideration of how both social and biological diversity are important in agroecosystem health and resilience, and is behind our adaptive management experiments to foster healthy and resilient agroecosystems, with food security as a key function. Because the story represents that of the many faculty and non-academic partners that comprise AMP, I will use the first person plural for most of the remainder of this paper and describe some of the challenges and opportunities in increasing agroecosystem health and food security that have been revealed in our research and outreach, but I accept full responsibility for what follows as my interpretation and representation of the work and ideas behind it.

Resilience is a property that includes stability in the face of small disturbances, but more importantly describes the capacity of a system to reorganize and maintain key functions when the environment changes to an entirely new state (Levin et al. 1998; Gunderson and Holling 2002; Biggs et al. 2012). Discussions of resilience in agriculture are typified by the insurance hypothesis, in which diversity results in redundancy and preservation of functions after environmental perturbation (e.g. Lin 2011). People have adapted agriculture and food production to the current range of environmental and social conditions in various ways. However, climate change predictions include profound environmental changes that may leave our current farming systems poorly adapted to a new and very different set of conditions. Such changes could be profound enough that they may result in an entirely different form and very different required functions in agricultural ecosystems, in both socioeconomic and biophysical terms, to achieve agroecosystem health and food security. Therefore, we will discuss increasing diversity in agroecosystems as a means of maintaining current ecosystem services and, along with self-organization, as a means of increasing the capacity of agroecosystems to adapt to climatic patterns that are expected to change in profound and largely unpredictable ways.

Framing agroecosystem health and resilient food security

Agroecosystems are occasionally referred to as if they are defined by a single crop (e.g. the soybean or rice agroecosystem) or some other component associated with agriculture (e.g. an irrigated agroecosystem). A systems perspective, however, requires recognition of people and all of our interactions with each other, with other organisms, and with our environment and at landscape scales in the definition. Agroecosystems typically include many farms and neighboring land uses, along with many people, both farmers and non-farming neighbors and community members. Although there is no clearly preferred geographic boundary that encompasses both the biophysical and social interactions in an agroecosystem, scales such as

watershed or production region would be more likely to encompass them than a single field, crop or farm.

Agroecosystem health is a concept that has been used to describe the functioning of an agroecosystem as it relates to meeting human needs. Views on what constitutes agroecosystem health range from the absence of deleterious organisms or contaminants to a set of functions that maintain or increase the capacity of the system to meet human needs (reviewed by Vadrevu et al. 2008). Many of the attempts at assessing agroecosystem sustainability or health focus on measuring the various ways in which agroecosystems are degraded or impacted, such as pesticide residues, erosion, biodiversity loss, or other typical impacts of human activity. More holistic descriptions of the relationship between structure and function of the system include a set of properties: productivity, stability, sustainability, equitability, and autonomy (Conway 1987, Marten 1988, Lopez-Ridaura 2002, Vadrevu et al. 2008). These properties are not mutually exclusive nor are they necessarily mutually supportive. For example, productivity might be increased in ways that are neither equitable nor sustainable, and likewise, equitability may be achieved in ways that are not particularly productive. But such tradeoffs are a result of specific management practices, and would be avoided or at least balanced in healthier agroecosystems to achieve each of the properties listed above. For example, a common tradeoff, often perceived as unavoidable, is between specialization in one or two commodity crops with high purchased inputs to achieve high productivity and associated negative environmental impacts that may compromise sustainability. Yet Davis et al. (2012) show that a more diverse and lower input cropping system can achieve the same productivity as the less diverse and high input system, including economic gain, with significant reductions in environmental impact; in this case choosing the more diverse cropping system would lead to greater productivity and sustainability and, therefore, greater agroecosystem health.

Proposed measurement of agroecosystem health has been in terms of indicators. These indicators represent capacities or capitals that can be measured at a point in time, but indicate the likely outcome or status of processes, where the processes over time determine agroecosystem properties and, therefore, agroecosystem health. Most definitions of agroecosystem health include both biophysical and socioeconomic dimensions (Vadrevu et al. 2008, Rao and Rogers 2008, Gomez-Limon & Sanchez-Rernandez 2010), which contribute in various ways to the properties listed above. For example, both may be equally important in determining productivity, because it takes human management skill and decision making to take advantage of biophysical capacity for production that is of human value. In contrast, socioeconomic dimensions may be more important in determining equitability, as the extent to which production and value are shared within the agroecosystem and among human communities at a range of scales, through trade. The biophysical and socioeconomic dimensions of agroecosystems have been well-characterized in terms of sets of capitals, which have been proposed to be the drivers of agroecosystem function (Rao and Rogers 2008).

Combining indicators to assess a current state of agroecosystem health in a structured way is challenging, but methods for calculating an index of agroecosystem health have been described (Vadrevu et al. 2008). The methods were described along with a case study of calculating and mapping the index (Vadrevu et al. 2008), so only a brief summary follows. Six key variables were proposed to describe a minimum set of conditions required to quantify agroecosystem health as a combination of the properties of agroecosystems described above (productivity, stability, sustainability, equitability): soil health, biodiversity, topography, farm

economics, land economics, and social organization. These key variables were quantified with measures of one or more attributes for each throughout a study area in Ohio. Data sources included remote sensing, digital elevation models, soil surveys, county auditor records, and a questionnaire administered to a sample of landowners in the study area. These data were combined to yield an agroecosystem health index that could be mapped for the study area. Combination of variables was by analytical hierarchy process, which has been used in a variety of multiple criteria and multiple objective analyses (Saaty 1980, 2000). The analytical hierarchy process modeling included two steps: 1.) combining the data at the pixel scale (30 m² in the case study) to represent the six key variables with normalized values, and 2.) combining the normalized key variables into a final normalized index, where each combination is a weighted sum of the normalized variables. Weights for the variables are calculated from a set of comparisons done by multiple individuals (with expertise in the topic, AMP research faculty in our case) between all pairs of variables, in which the variable that contributes more to the overall objective or concept (in our case, agroecosystem health as a combination of four properties: productivity, stability, sustainability, equitability) is identified along with an estimate of the difference between the variables in that contribution. Geometric means of these individual scores were combined into consensus weights, the weights were applied to the data, and the resulting index was mapped. Spatial patterns in the index were an emergent property of combined socioeconomic and biophysical conditions, none of which were apparent in any of the underlying data for the key variables. Furthermore, the agroecosystem health index and its underlying data can be analyzed for a particular landscape so that policymakers, educators, service agencies, organizations, and the people who live in the area can find and evaluate opportunities to improve agroecosystem health.

The initial development of an agroecosystem health index relied on extensive spatially referenced data that is not easily collected or generally available. In particular, the variables that measured social organization required a detailed survey of landowners throughout the area for which the index was being calculated. AMP researchers have since developed an approach for calculating the index based entirely upon publicly available data (Table 1). This newer version includes the same key variables as those used in the earlier study (Vadrevu et al. 2008), but the data used to measure each of these key variables was derived from public datasets. For example, social organization was calculated from four of the variables that are included in the US Census,

Table 1. – Variables and analytical hierarchy weights used to calculate an agroecosystem health index for Northeast Ohio using publicly available data sources.

Key Variable	Source	Variable weights for	
		Key Variables	Index
Biodiversity	NASS ¹ Crop Data Layer		0.1865
Topography	USGS ² Digital Elevation Model		0.0692
Soil Health	USGS SSURGO ³		0.1359
Soil organic matter %		0.35	
available water capacity		0.2	
Land capability classes (x100)		0.45	
Farm production value ⁴	USGS SSURGO		0.18904
Land value	School district land market value		0.19263
Social organization ⁴	US Census		0.22674
Education (US Census Block)		0.1	
Number of farms (US Census Block Group)		0.3	

number of farm operations (US Census Block Group)	0.4
<u>proportion of agricultural land, conservation and wetlands</u>	<u>0.2</u>

¹ National Agricultural Statistics Service of the US Department of Agriculture. ²US Geological Survey. ³US Department of Agriculture, Natural Resources Conservation Service, Soil Survey Geographic Database. ⁴The Ohio Current Agricultural Use Value (CAUV) is a monetary value that represents the value of land for farming. It is calculated as a function of soil type, so we used the SSURGO soil type data to calculate the CAUV for our study. ⁵Social organization is hypothesized to be associated with variables that include education level, assumed to be associated with communication and democratic process, the prevalence of farming, and it's association with conservation as an indication of healthy relationships between farmers and neighbors.

at the finest resolution available. Table 1 provides the variables used and their sources along with the weights that were derived from analytical hierarchy process modeling and used to calculate the index, and Figure 1 displays the resulting index for a NorthEast Ohio region. The region is characterized by temperate climate, enough rainfall that irrigation is rarely used, flat terrain to gently rolling hills, and a wide range of soil types and naturally occurring plant communities. Agriculture represents approximately 40% of the land area, along with large cities such as Cleveland and Akron. Markets are diverse, including commodity to retail, and farm scales and enterprises are diverse as well, including horticultural and agronomic crops, pasture, and livestock, particularly dairy. As in Vadrevu et al. (2008), the key take-home message from the index is that both the socioeconomic and the biophysical dimensions of the agroecosystem are required for a complete measure of agroecosystem health, and agroecosystem health varies spatially as a result of the combination of these factors. For example, one can find both urban areas (e.g. greater Cleveland, top center in the figure) and rural areas (e.g. the northeast part of the region, top right in the figure) that score relatively low in agroecosystem health index but for different reasons. The northeast part of the region has a clay fragipan layer that reduces drainage and water infiltration, creating a challenge in maintaining high soil quality for production, although many very successful farms are in this area. On the other hand, Cleveland has large areas of impervious surfaces and low social organization and low farmland production value scores. Areas scoring higher in agroecosystem health, likewise, may vary in the quantity of different capitals that lead to agroecosystem health.

How food security is embedded in agroecosystem health

Food security has evolved as a concept since a fundamental right to food was recognized in the 1948 Universal Declaration of Human Rights. The evolving definition of food security has been informed by further elaboration on the right to food (recently reviewed by Kuhnlein 2014), food sovereignty (recently reviewed by Edelman et al. 2014) and the relationships between the two (Beuchelt and Virchow 2012). For example, the 1999 Committee on Economic, Social and Cultural Rights (CESCR) description of the right to food in **General Comment 12** describes the realization of the right to food as a state of food security: “The right to adequate food is realized when every man, woman and child, alone or in community with others, has the physical and economic access at all times to adequate food or means for its procurement”. Key elements of the evolving definition of food security include sufficient quantity and quality of food for everyone at all times. Sufficient quantity is met if the means of production or procurement are consistently available to all, with consistency implying sustainability of production and distribution including its social, economic and environmental dimensions. Sufficient quality adds a host of additional considerations (i.e. what is meant by “adequate food”)

including nutritional composition that supports a healthy active life, and satisfying cultural preferences through self-determination of the food system at various levels of organization from individual to household to community to national. We hypothesize that sufficient quality and quantity, or at least the means to procure sufficient quality and quantity if production is equitably shared and sufficient to acquire both, could be expected from a healthy agroecosystem.

Each of the agroecosystem properties described above is critical in food security, and we've described agroecosystem health as a combination of all four. Productivity must be above a threshold set by human needs for food. Stability and equity in production, including equitable access to production resources, are needed to ensure consistent supply over short-term intervals. Sustainability implies that production and equitable access are sufficient for long-term food security. Autonomy is the ability of people living within a particular boundary to meet their own needs for food, without having to rely on external sources for either food or the means of producing it. If production within a given agroecosystem is consistently sufficient for the population within, and does not require external inputs, and the food supply from external sources is not reliable over time, then autonomy would be a means to food security. However, if food supply is variable and not sufficient at least at some times, then autonomy would not be a means to achieving food security. Instead, capacity to trade for food from other agroecosystems becomes an important requisite for food security. The most food secure point on a continuum from complete autonomy to entirely reliant on external sources for food, a function of whether local or distant supply is most frequently at risk, is probably more important than capacity for either autonomy or trade. Climate change predictions include a number of challenges to food production such as drought, flood, and severe storms that could decrease productivity in any given location. The frequency, duration, and location of these challenges, however, are not predictable in current climate change models, so the ability to achieve both autonomy and capacity to trade for external food supply may be the prudent strategy for food security.

Conceptual linkage between agroecosystem health and resilience

Biological diversity is considered to be a driver of the agroecosystem processes that lead to agroecosystem health. Diversity in general is a key feature of resilient systems, because of the reliance of adaptation on sufficient diversity, and selection upon it. Human and cultural diversity play a role in how we manage the land in agroecosystems. Traditions, histories, values, and economies all become important elements of diversity that are subject to selection under profound environmental change, similar to selection on biological diversity. Therefore, both biological and cultural diversity should be considered to be key elements of the potential for adaptation, along with self-organization capacity in both biological and cultural dimensions of agroecosystems.

Biological diversity

Biophysical dimensions of agroecosystems focus on natural capitals, which encompass a wide range of attributes including soils, water, nutrients, climate, and biological diversity. Biological diversity is fundamentally genetic and occurs both within (biochemical, structural, phenological) and among species at population and community levels. Biological diversity occurs at spatial scales from millimeters to continents, depending on the organisms involved, and changes at temporal scales of minutes to years. It is relevant to agroecosystems primarily in how it influences key functions of yield and productivity. Both literature reviews (e.g. Altieri 1999,

Lin 2011) and specific examples (e.g. Davis et al. 2012, Boody et al. 2005) have highlighted the important role of agricultural crop diversity in agroecosystem productivity and stability.

Large-scale production of a small number of crops represented by very few cultivars, although economically efficient in US agroecosystems, is clearly not a route to biological diversity. Biological diversity can be increased within agroecosystems by increasing the proportion of land area in unmanaged and minimally managed habitats, which are typically more biologically diverse, and by increasing the diversity of the crops and livestock produced. For example, diversity might be enhanced by farming at a wide range of scales, matching variation in what is produced with the natural and physical variation in the landscape as well as its social and cultural patterns. Increasing diversity of managed crops and animals at these same scales could be expected to result in greater biological diversity, more species rich foodwebs, and improved ecosystem services that rely on this diversity. For example, biological control of insects could be enhanced by a complex of natural enemies with a broader range of requirements, such as pollen and nectar, than a single crop could provide.

Mechanistically, crop diversity increases available functional traits to increase biotic interaction and ensure consistency in production despite disturbance (Hajjar et al. 2008). In particular, crop diversity can enhance regulating ecosystem services such as pollination, pest and disease control, soil health, and CO₂ sequestration, each of which contributes to productivity and stability in the short term and sustainability and adaptation in the longer term. For example, preserving soil health and preventing erosion could contribute sustained ecosystem services in the short term and provide a greater capacity to reorganize and adapt under future environmental change. Biotic interactions resulting from crop diversity can be very complex, but models of such interactions are considered to be feasible (Médiène et al. 2011) and the data and models needed to manage this complexity are accumulating.

Farm enterprise diversity, with variation in what is produced providing greater landscape heterogeneity in plant populations at scales of m to km, can increase biological diversity overall and is, therefore, a bridge to the cultural diversity that will be discussed next. This enterprise diversity can arise from individual farmers and land managers engaging in more diversified farming or more landowners occupying smaller areas and, even if specializing individually, producing many different kinds of crops and livestock. In fact both were evident in the area we picked for the case study of mapping an index of agroecosystem health (Vadrevu et al. 2008). The study area was selected by observation from an airplane flying at 600-900 m. A landscape pattern that transitioned from very large expanses of single crops with little else around them to one of much smaller fields containing a greater range of crops, including pasture, and with more forested and other minimally managed areas among them, was clearly evident. We knew from previous work that an associated pattern was large-scale cash grain producers in the areas with larger fields of few crops, and to a mixture of Amish and non-Amish farm owners with smaller farms and more integrated livestock in the areas with smaller fields.

Cultural diversity

Farmers in the United States have been declining in both number and diversity for many decades, following a long-term pattern of farm consolidation and people leaving farms for cities. Approaches to farming in the Midwestern US have largely bifurcated as a result of economic pressures on farmers, who tend to experience relatively constant prices for commodities while

the cost of inputs increases. Farmers require some means of achieving a successful business model in response to these pressures.

One approach taken by farms that have typically been held within families for generations and that have continuously adopted new agricultural technology has been to become larger by acquiring surrounding farms that did not grow or transition within families. The typical business model is to specialize within a few commodities, for which prices have generally been constant, and deal with the rising costs of inputs (e.g. fertilization or feed, pest control, equipment, genetics) by expanding and maximizing yield per acre in the case of crops, or per animal in the case of livestock, and per farmer in either case. Farmers adopting this approach must be excellent managers of technology and inputs, with excellent business acumen to select and use both equipment and purchased inputs in ways that will maximize yield and profit over large and continuously growing land holdings with minimal numbers of relatively skilled, and therefore expensive, employees. In cases where hand labor is required (e.g. poultry processing, fresh vegetable production, large dairy management) the owner must be adept at managing a large labor force doing relatively unskilled (although often to exacting specifications) work at minimal wages, often by an imported and seasonal workforce. Producers in these systems can innovate in process engineering, human resource management, small modifications to equipment, and the use of technology and production inputs. However, most of the innovation in their production system takes place at global scales within the corporations that supply the equipment, inputs, and services that are absolutely essential to this large scale and prescriptive approach to farming.

Other approaches to farming, typically stimulated by a lack of the extensive land and built capital (buildings, very expensive equipment, etc.) required to achieve economies of scale, provide an alternative to expansion and large-scale production: seeking a unique and profitable niche that permits specialization at small scale (e.g. organic dairy, wine, artisan cheese, rare spices); or seeking an *economy of scope*, which includes diversification and the ecosystem services outlined above. Production inputs tend to be refocused on labor and expertise of farm managers rather than purchased technology. These approaches are open to a wide range of new farmers, whether they have inherited land and have been taught the needed skills from an early age or are entirely new to farming but may be motivated by factors such as lifestyle and land ethic and may choose to farm in or near urban centers. Innovation is occurring as a result of new ideas and new approaches brought by people who are relatively new to farming. Although risk levels in these enterprises may vary widely and many of their experiments may fail, the unconstrained thinking and experimentation is likely to produce new innovations. Technology still plays a role in these production systems, for example extending the growing season with unheated high tunnel (typically aluminum frames covered with heavy translucent plastic to serve as an inexpensive version of a greenhouse) production systems and new crops or livestock breeds. But individuals may play a greater role in developing and adapting technology in these less prescriptive systems through on-farm innovation. This increase in smaller and more diverse farming approaches may increase resilience in agroecosystems over time.

The history and traditions of people dwelling in the agroecosystem can be quite relevant to what is produced, a function of both the human and social capitals that lead to concentrations of particular kinds of production. Examples range from long-standing traditions of indigenous peoples that have been maintained over many centuries to more recent associations between members of a diaspora and a particular landscape. Such groups can be well organized as in the

current member organizations of the international La Via Campesina or Amish communities in the United States, or more loosely organized socially and with less outwardly observable group identity. A few examples of the latter from our region include cabbage growers of Danish heritage in the Finger Lakes Region of New York, vegetable producers of Dutch heritage on high organic matter muck soils in Ohio, onion growers of Italian ancestry on muck soils in New York, and dairy farmers of German and Swiss descent in Northeast Ohio. Although specifics of agricultural practice may change over time, the ties between groups and what they produce may remain in agricultural communities and can lead either to specialization and a reduction in crop or animal diversity or to maintaining diversified farms despite economic pressure to specialize and grow in size. Therefore, the contribution of cultural diversity in farmers to agroecosystem health may depend upon the extent to which it supports enterprise and biological diversity, and contributes to social organization among farmers at landscape scales.

Self-organization in agroecosystems

A key feature of agroecology as a production paradigm is managing agroecosystems to maximize ecosystem services that accrue from naturally occurring ecological processes. Specialized and simplified agricultural production systems, in contrast, must supply inputs that replace ecosystem services because the biological diversity in the system is insufficient or cannot be organized in ways that provide them. An agroecosystem that is managed in ways that achieve stable and sustainable production would likely include self-organizing and naturally occurring processes to achieve these ends. Self-organizing biological communities generally require sufficient functional diversity to fill niches across trophic levels in complex and stable food webs. Productivity in diverse systems can result from niche saturation, all niches being filled by organisms that are well adapted to their niche. Further contributions in diverse food webs include trophic cascades of both bottom up and top down regulation of agriculturally important population dynamics and cycles, providing the regulating ecosystem services that permit food production with less reliance on external inputs like pesticides (Lin 2011).

Self-organizing social and economic systems in globalized commodity production are often suppressed by top down provision of inputs and centralization of key supply chain functions, such as aggregation, transportation, processing, and marketing. In such systems, organization is imposed by global corporations, for example via sales of a prescriptive set of products and technologies (seed, fertilizer, pesticides) needed to maintain the production system. Social organization in communities of farmers that share this production system, however, may support it with social and behavioral norms that place high value on conformity. An example of top down organization is a reliance on pesticide inputs to control pests. International corporations with global production and distribution systems supply most pesticide inputs. A typical outcome of reliance on pesticides is the evolution of resistance in pest populations. If no alternative pesticide option is available, then individual farmers who have resistant pests and rely on effective pesticides to control them can be at risk of substantial losses. Their solutions do not arise from within their farms; rather they must be passed down in the form of new pesticide technology from international corporations. The system itself, therefore, is regulated not by self-organizing properties of diverse entities at local scales but by relatively few global firms that rely on international supply chains, and periodic introduction of new technology (Hoy 2009). When key inputs such as new cultivars or fertilizers must be obtained from global corporations to maintain production, autonomy, equitability, and self-organization of production decline. Lack of such inputs, or shifts in the environment, such as emergence of pest resistance or water

availability, that require rapid change in available inputs, such as new pesticides or irrigation systems, can put farms that rely on them out of business. Profit margins in large scale agriculture tend to be very slim, a factor that drives continuous expansion as a means to ensure sufficient profits to maintain the farm enterprise. When the means to adapt to sudden changes in the cost or availability of needed inputs are not under the control of farmers, adaptation does not occur at the level of farms or even regions, and may not occur quickly enough to keep farms in business. And some of the inputs that farms have counted on in the past, such as cheap and abundant fossil fuels, water, and consistently predictable climate, are widely predicted to become less reliable in the future.

Large-scale systems tend to be self-reinforcing, however, to the detriment of maintaining diverse production capabilities. An example is in large scale diversified vegetable production, such as that found in the Salinas valley of California, Arizona, Texas, Florida, and in smaller production areas in other states including the Great Lakes Region and Canada. Marketing of these vegetables has evolved to a system in which buying and shipping is least costly if all items can be purchased from one location. The result, however, is that in northern production regions like Ohio, production that could be taking place year round and delivered locally, is restricted to a few months when all items are available. Capacity for local production, therefore, is under developed and poorly used, *not because we lack the capacity* but because it doesn't fit well in national and global supply chains. It remains to be seen how quickly this unused production capacity could be enhanced and redirected if food supply from more distant sources becomes less reliable. Alternative production systems relying on economy of scope may provide new opportunities to explore self-organization of markets, innovation, and relationships among farms and other firms at local and regional scales. These are the kinds of qualities that would become necessary for a system to adapt to an unpredictable and uncertain new set of environmental and social conditions.

Opportunities for enhancing agroecosystem health for resilient food security

Based on the conceptual model of agroecosystem health described above, and how food security is expected to emerge from healthy agroecosystems, our approach to managing agroecosystems for both health and resilience has focused on promoting self-organizing social network behavior to build greater farm enterprise diversity into agroecosystems. A current opportunity appears to be supporting a diverse population of entrepreneurs who can launch a wide range of innovative and new production or agricultural supply chain enterprises at a range of scales, but especially very small scales. These small enterprises, typically not engaged with commodity production but rather differentiated products sold on shorter and more localized supply chains, could increase diversity in agricultural production (e.g. Goland and Bauer 2004). Entrepreneurship promotes several features of resilient complex adaptive systems, at least in economic terms: dispersed interaction, continual adaptation, and perpetual novelty. Furthermore, entrepreneurial approaches are an important feature of the literature on sustainable agriculture. Therefore, we have experimented with enhancing entrepreneurship in agroecosystems as a means of increasing diversity in both cultural and biological dimensions. Our basic approach (Hoy et al. 2012) has been to facilitate social networks among entrepreneurs at the business planning stage. We have developed online tools for identifying how their planned enterprises could build supply chains, rather than the individual links (Figure 2, and see localfoodsystems.org). Social networking tools then encourage and promote business plans for collaborative business networks rather than just individual businesses. Therefore, our social

networking tools are designed to enhance self-organizing entrepreneurial ecosystems that provide new adaptive capacity. Our hypothesis is that such self-organizing entrepreneurship will support more diverse food supply chain enterprises, more landscape diversity in production, and improved agroecosystem health.

Increase diversity of people and enterprises in agroecosystems

Research in business and economics has identified strong social networks as a key element of entrepreneurial ecosystems, featuring successful and active entrepreneurship, particularly in many small businesses at local and regional scales (Neck et al. 2004, Cohen 2006). Associated benefits to agroecosystem health should include biological diversity, accruing from greater landscape heterogeneity in crops and production systems at a range of scales from very local to regional. A common feature of such smaller scale and more diverse production systems is a reliance on economies of scope rather than economies of scale.

We hypothesize that self-organizing behavior in social networks can promote production diversity and associated economies of scope. Of equal importance to crop and livestock production diversity is greater diversity of participants in this economic activity. Given the importance of equitability as one of the properties of agroecosystem health, our hypothesis is that internet-based social networking tools that are accessible to anyone who can find an internet connection, will promote open-source innovation and development of inclusive cooperative business networks. Greater and more equitable access to tools that assist entry to the economy may also contribute to the self-organizing behavior of economic systems that enhance diversity in agriculture, ultimately improving agroecosystem health and resilience, and improving food security via more consistent access to fresh food at local and regional scales. Tests of the hypotheses proposed above will require adaptive management research. However, use of the social networking tools we have introduced to stimulate entrepreneurial ecosystems may eventually allow us to make regional comparisons as new supply chains develop.

Application of diversity concepts to large, economy-of-scale farming is more difficult than for small and diversified economy-of-scope farming. Possibilities may arise from new agricultural technologies. Precision agriculture, for example, is essentially a means of managing agricultural inputs in areas that are small enough (1 m^2 or smaller) to be effectively uniform, removing heterogeneity that typically results in less than optimal results when inputs are applied uniformly over much larger areas such as an entire field. In general, precision agriculture technology is shifting from an emphasis on monitoring yield at harvest, meter by meter, and adjusting subsequent inputs in future plantings, to more frequent monitoring during crop development and adjusting inputs from the planting stage on. Whereas adjusting application rates of inputs like fertilizer or pesticide has been available technology for some time, newer technology is being developed for applications like choosing from among several cultivars based on conditions at the specific location for each seed in the furrow. By doing so, biodiversity within fields could be increased, perhaps creating greater incentive for more genetic variation within cultivars or increasing the number of crop species within a field, reserving uniformity for key characteristics such as days to maturity and suitability for machine harvest. If, and perhaps only if, farmers regain a means of tailoring the diversity in their crops to the conditions on their farms, then the technology could increase both biological diversity and farmer innovation across multiple scales.

As noted above, work in AMP has focused on increasing the social organization and self-organizing behaviors in building local economies associated with agriculture and food production. Tools we have used include social media, and have been designed to connect entrepreneurs along supply chains to form collaborative business networks that meet local needs with local supplies. The rationale is both to take advantage of economic opportunity in new and shorter supply chains and to provide the economic support for more diversified agriculture, on a wider range of farming scales. The self-organizing collaborative business networks we are supporting with social media tools are intended to increase social organization in agroecosystems, as well as biological diversity and autonomy via local production.

Impediments to the social organization we are encouraging arise from the typical approaches to economic development applied to agriculture, which place greatest value on large scale, export-oriented production and global competition. Entrepreneurs are often advised to maintain confidentiality, under the assumption that they may have intellectual property that would be lost if they share ideas or collaborate with other businesses. The focus of business planning is on competition rather than collaboration; for example, the standard US business plan contains a section on the competitive situation, but no section for collaborative arrangements with supply chain partners. Furthermore, the typical entrepreneurship service provider, needing to meet standards and quotas for impacts on such metrics as jobs and income, tends to focus on relatively large firms poised for global growth rather than many small businesses engaged with local import substitution. Entrepreneurship is often cast as requiring a drive to grow continuously, rather than grow to a point where the business is stable, providing jobs, meeting needs, and performing a useful function in a business ecosystem. Likewise business ecosystems are often conceived as the set of interacting businesses that support a single large and dominant firm (e.g. Iansiti and Levian 2004) rather than a set of collaborating businesses that share economic power and trade along a supply chain on relatively equal terms. Examples of the latter do exist, for example Zingerman's Community of Businesses in Ann Arbor, MI, a collection of eight independent food production/preparation businesses with synergy in marketing; Great Lakes Brewing Company in Cleveland, OH, which partners with a number of farms and food producers to recycle spent brewing grains into food products for their restaurant; and a number of local to regional food hubs such as the over 150 businesses associated with the Detroit Eastern Market. Our experience has been, however, that despite the logic of collaborative business networks in reducing waste, increasing efficiency and markets, and reducing risk, business owners and entrepreneurs are reluctant to enter into such business relationships because the required levels of trust are challenging to establish. Teamwork and collaboration seems to be valued within firms, but less so among them. The social media tools we are developing, like most social media sites, gain value with more users. The combination of this lag in use, inherent in social media, and the tradition of competition and low trust in business ecosystems needs to be overcome to develop self-organizing entrepreneurial ecosystems associated with agriculture and food.

Social organization that ensures a balance between autonomy and trade for needed goods such as food may require different and larger scale means of gaining self-organizing capacity for adaptation to environmental change. As noted above, the system that organizes and facilitates large-scale farming is not self-organizing below very large scales, and adaptation depends on very few organizations delivering new input technology and products. The system lacks diversity and as a result becomes fragile when such key inputs as fuel or phosphorus become limiting or when the climate changes in unanticipated ways or extents. Localities and regions

that depend on distant supplies may become increasingly at risk if these supplies are disrupted. But local and regional systems could also be at risk if climate events such as large storms threaten their production capacity. If production capacity is greatly reduced at local or regional scales due to extreme weather events for example, then people in those areas will be dependent upon other regions for needed goods. The social networks needed to establish these more extensive regional to international scale networks may be more difficult to develop, particularly with justice and equity among all food producers and consumers, than more localized networks. The internet, however, removes many of the impediments to personal communication that come with larger scale. Enhancing the balance between local production capability and efficiency of trade and distribution across scales, particularly in adaptive and self-organizing ways, will be critical to evolving resilience in food security.

Focus on the diversity-productivity-adaptability nexus

Interdisciplinary research is needed to test the hypothesis that self-organizing social and economic activities in more diverse agroecosystems will increase both productivity under current conditions and adaptive capacity under extreme changes in the environment. Simulation of these scenarios would require a very interdisciplinary mix of spatially explicit biophysical models that could predict output of particular production systems under various climate scenarios and agent-based models of economies and human population behaviors that could explain and predict levels of self-organization, diversity, and their basis in social behaviors. Empirical studies would require adaptive management with repeated cycles of a sequence of planning, implementation, observation or monitoring, and analysis. One could expect the experiment to influence the system over time, given the scale and potential impact of experiments, like the introduction of social media tools described above, on agroecosystems.

Transition pathways are currently clear for expansion and consolidation of farms, but not for diversification, particularly once farms have grown to a very large scale. Farm consolidation has taken place for decades, increasing economies of scale and skewing the size distribution of farms to the point where a very small percentage of farms produce a very large percentage of farm output in the US. Information on how to specialize, consolidate, and expand farms is much more prevalent in the US than information on how to split and diversify farms. At least in Ohio, commodity farmers occasionally diversify a small area near a busy road or intersection to experiment with direct sales of vegetable or fruit crops, and such experiments may lead to further diversification if successful, but little data exists on trends in these activities or long term impact on land use and farm management. A traditional means of reducing farm size has been division of farms among family members when a farm is passed along from one generation to the next. Given the advanced average age of farmers in the US (58.3 years according to the 2012 US Agricultural Census), farm transfers could become more common in the coming decade or two. However, farms are often sold and either converted to another land use or added to a larger farm. Therefore, farm transition strategies, policies, and associated research and education programs are needed that clarify options for converting, through sale or inheritance or other means, a large specialized farm to multiple smaller and more diverse farms. Sustainable agriculture education programs will be important in preparing a next generation of farmers for the entrepreneurial and more complex management required of such diversified systems, more so than specialized education programs that prepare individuals to maximize the use of technology for a specialized and restricted set of commodities. Support is needed for research grant programs such as the currently available USDA Agriculture and Food Research Initiative (AFRI) Small and Medium-

sized Farms, Food Security, Agroecosystem Management, and Organic Research and Extension Initiative, and the USDA Sustainable Agriculture Research and Education programs to encourage the successful growth of more diversified production and distribution systems.

Examples of recent research by students following a specialization in Agroecosystem Science of The Ohio State University's Environmental Science Graduate Program will highlight some of the research questions that are important in shifting perceptions regarding production scale. Students have begun to explore what changes in production are possible, working within the boundaries of land already in crop production or in other managed systems, to shift the diversity and productivity of agricultural ecosystems in Ohio. In one such study (Kolbe 2013), scenarios for temporally and spatially diversified production, based on agroecological design, were developed at 3 scales (approximately 0.1, 5.25 and 42.5 ha). The designs were then used to estimate yield from a scenario in which these designs would be used for production wherever they could fit in contiguous land that was either already in agricultural production or in other land uses suitable for production, such as managed turfgrass (including residential and commercial lawns). The scenario was developed by "placing" the three designs, from largest to smallest in sequence, on the landscape of NE Ohio. The yield from each design, in kcal and nutritional components of kcal produced, was then estimated based on methods developed for foodshed modeling (Peters et al. 2008), which include such factors as soil and topography data (Figure 3). Estimated yield from this alternative and greatly diversified production, and nutritional composition of that yield, could then be compared with existing yield and nutritional composition afforded by the region's current production (predominantly corn and soybean rotations, followed by dairy, horticultural crops, and a wide range of other crops and livestock). The analysis demonstrated that at least 4 times the number of kcal could be produced by the diversified scenario compared to what is currently produced, with a nutritional composition that would be higher in vitamins (A, B6, C), minerals (Ca, Mg, K, but not Fe) and fiber, about the same in protein and carbohydrate, and lower in fat. Of course, the research question was about what production is possible on this landscape, not what it would take to produce such a change in land use. That would include a host of profound economic and social changes, such as land ownership or access, labor, equipment and livelihoods in such a production system.

Another recent project focused on what could be produced if private land that was not currently being used for food production were to be shifted to production of fruits and vegetables (Kerrick 2013). The concept explored in this study was usufruct, the productive use of another person's land. This study examined the land resources available across a rural to urban gradient in Ohio under both public and private ownership. The proportion of public and private land that could be usefully converted to fruit and vegetable production, based on land capability factors (solar exposure, soil quality, slope, and water access) was calculated first. Then the potential annual fruit and vegetable production was estimated within randomly selected study sites of 500 m radius along the rural-urban gradient, based on the land capability factors for both public and private land. Potential for meeting dietary requirements for fruits and vegetables was then estimated within these study sites. As expected, rural areas have few households and abundant vacant land on which production is possible, whereas urban residential areas have many households and little available public or private land. As a result, the vegetable needs of rural residents could be met through production on available private vacant land within their neighborhood many times over, whereas only approximately 2% and 8% of the urban and suburban population's needs could be met by production within their residential areas, respectively (Figure 4). Interestingly, in urban commercial areas with relatively few residences

but relatively abundant vacant private land, approximately 20% of the residents' recommended vegetable intake could be produced. These results are a good example of the variation in feasibility of food autonomy at very local scales in the US.

Conclusions

Predicted climate change impacts, including shifts in growing seasons and more extreme and unpredictable severe storms, droughts and floods, could require system wide change in food production, distribution, and consumption. The studies and activities described above begin to address what is possible with diversified production and begin laying out alternatives that could be explored for a transition to more resilient agricultural and food systems. Agroecosystem health can be increased, at least in agroecosystems that have become dominated by large-scale and specialized production, by increasing the diversity of production within them. A shift in focus on managing diversity in an agroecosystem rather than managing production of any particular commodities would be a good first step. Accounting for productivity in such systems should include the value of ecosystem services - an accounting stance that would clarify the lack of efficiency in ecological terms of many current production systems. In a more detailed accounting, farmers would seek additional payoffs by augmenting ecosystem services, managing biological diversity in production systems to progress toward this goal.

Social and cultural diversity could add to agroecosystem health if accompanied by sufficient self-organizing capacity to spur innovation. Our work with social media to support planning for increased supply chain diversity, has highlighted several obstacles to be overcome. The typical focus of economic development currently is not supportive of collaborative business networks that localize supply chains with diverse enterprises. Entrepreneurial training and support for collaborative business plan development, with greater efficiency and lower risk in a diversified business ecosystem would contribute needed self-organizing capacity at local scales. A combination of naturally occurring biological, crop, livestock, and business enterprise diversity could engage a diverse set of livelihoods, perhaps supporting many cultural traditions. Cultural and social diversity that is sufficiently harmonious to self-organize in support of the biological diversity needed to achieve agroecosystem health and resilience, will be key to resilient food security as a property that emerges from healthy agroecosystems.

Systems-oriented agroecology research that creates a better understanding of managing diversity, rather than replacing it with purchased inputs, would help to achieve healthy and resilient agroecosystems. Both educational programs that train scientists and practitioners and grant programs that support ongoing work in this area are available, but remain in the minority at least in the US. Particularly valuable would be a focus on the mechanistic relationships between social and biological diversity, including self-organizing processes and their contributions to the properties of agroecosystem health.

The global economy is functioning as expected, with large-scale enterprises that find the greatest economies of scale wherever they can be found. Its function is to ensure low prices, but it also results in concentration of wealth. The global economy is not currently organized or regulated in ways that ensure food security in Ohio or any other particular place. This is evident in that approximately 805 million, one in nine of the world's population, were chronically undernourished in 2012-14 (FAO, IFAD and WFP 2014) despite abundant production. And despite what are generally considered to be low food prices in the US, an estimated 16% of households in Ohio were food insecure in 2011-2013 (Coleman-Jensen et al. 2014). Our

economic opportunity is to meet basic needs that the global economy does not meet, such as food security, at local scales and via an alternative business ecosystem that supports agroecosystem health.

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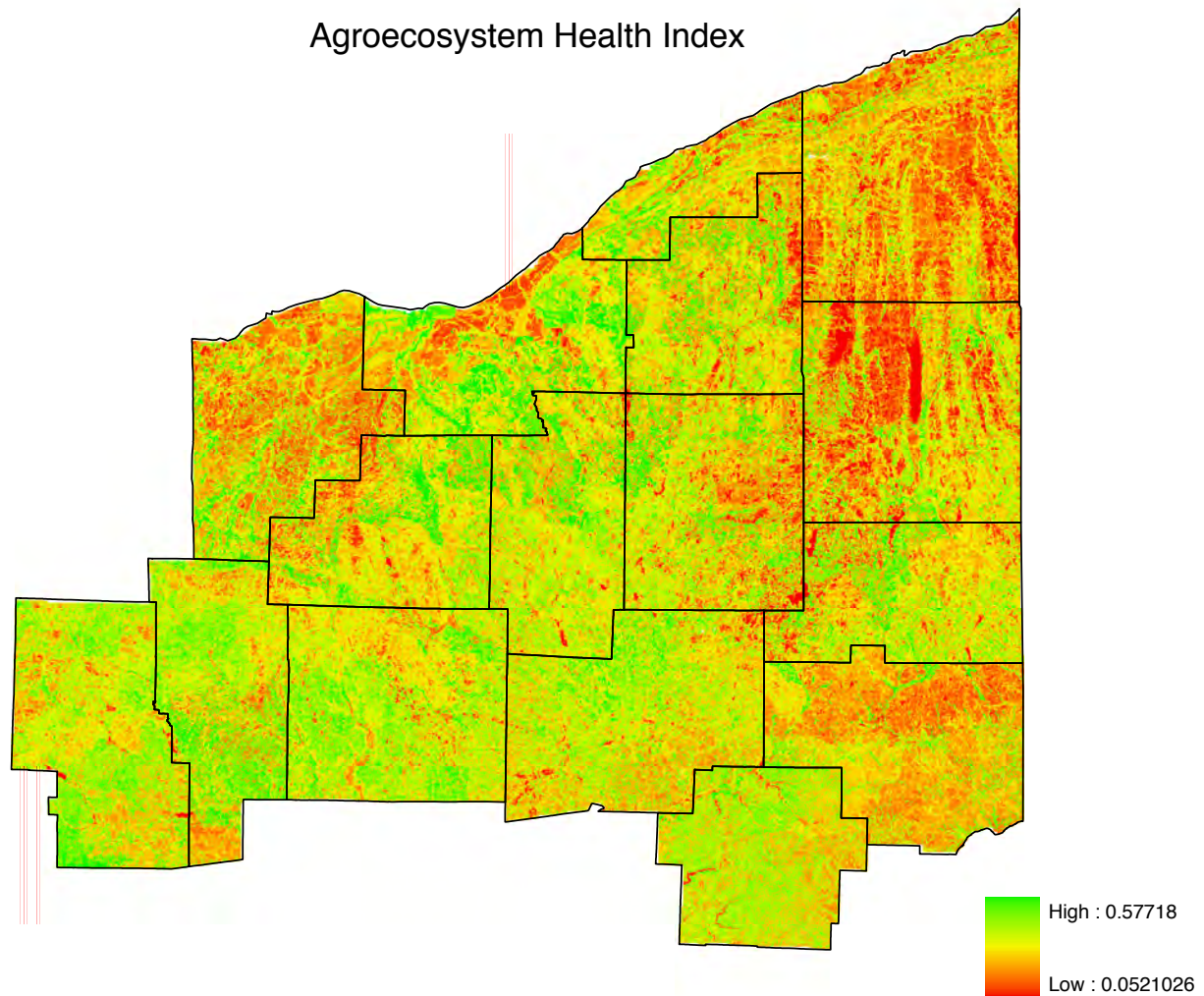


Figure 1 – Agroecosystem health index calculated for the 16-county Northeast Ohio region using publicly available data from the US Census, Agricultural Census, National Agricultural Statistics Service, and US Geological Survey following methods in Vadrevu et al. (2008). High and low are calculated according to a weighted combination of the socioeconomic and biophysical conditions in the region that are related to the properties of agroecosystem health.

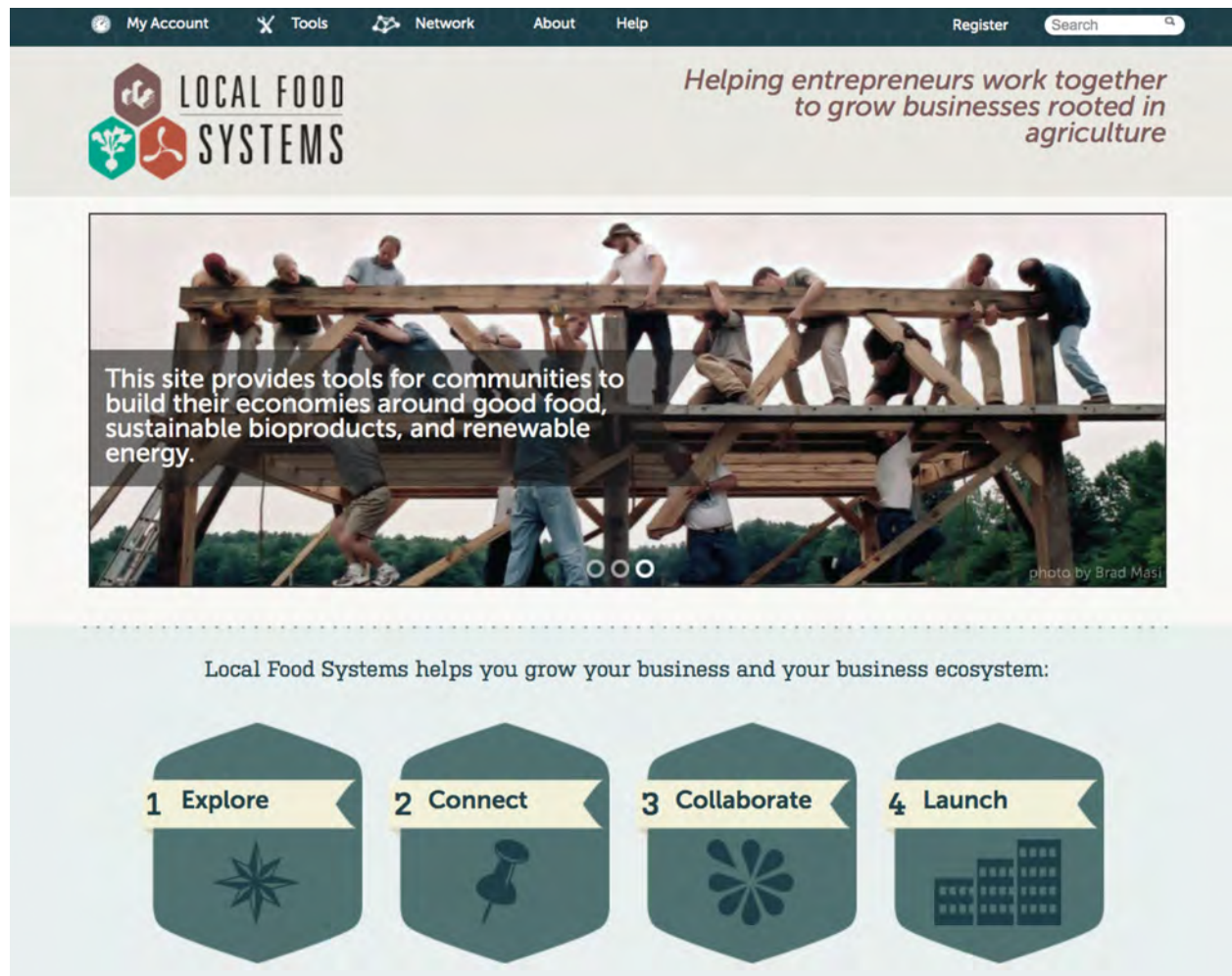


Figure 2. – Home page of localfoodsystems.org, a social networking site designed to assist with planning local supply chains.

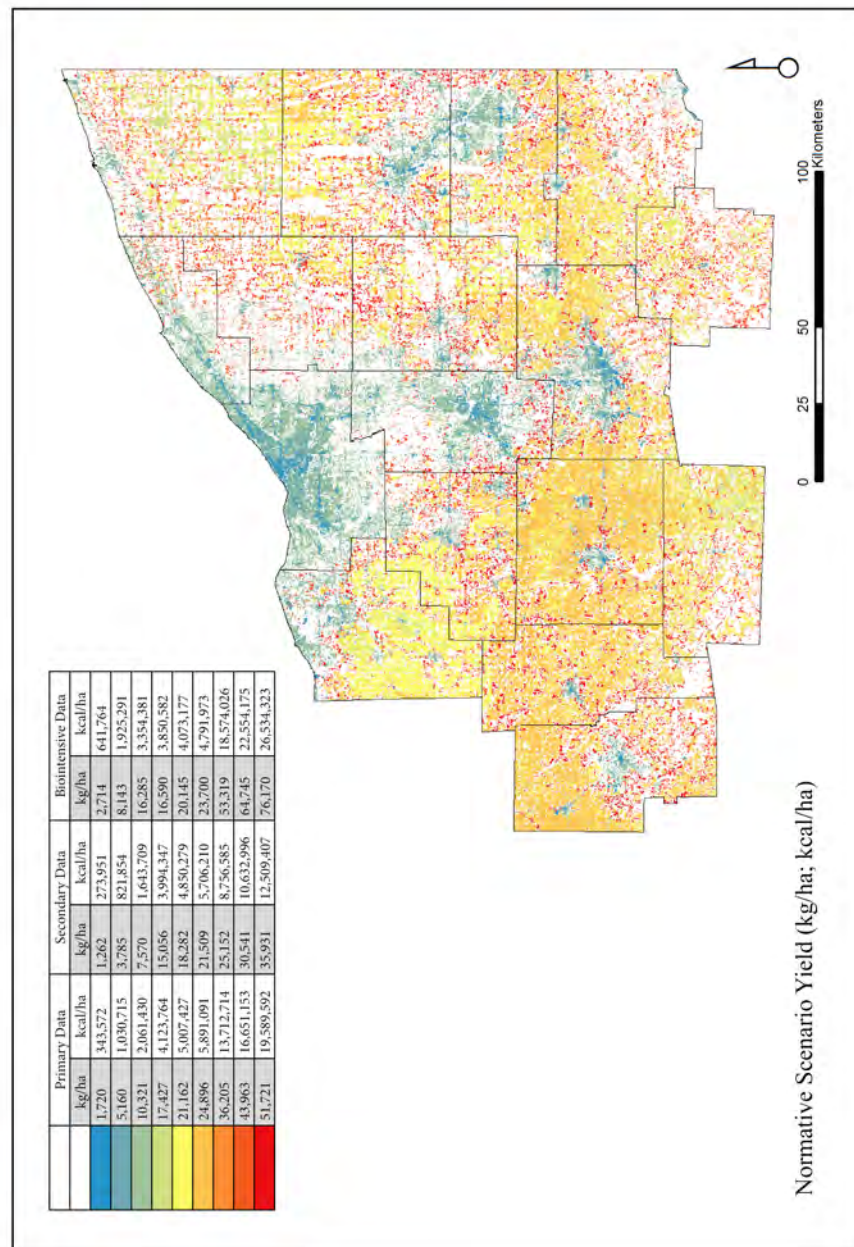


Figure 3. – Estimates of potential yield in Northeast Ohio from contiguous land that is either in agricultural production or in a soil capability class that would permit production (i.e. cleared land with slope and soil class suitable for production).

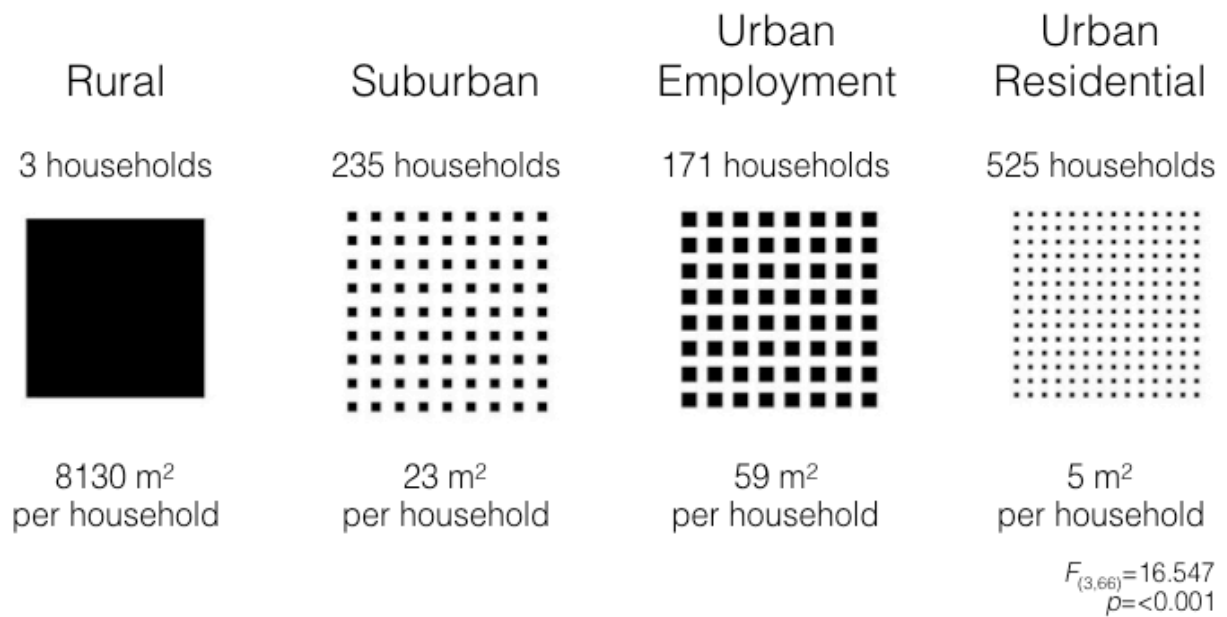


Figure 4. – Differences in the area of private, vacant land that is suitable for vegetable production that is available per household in neighborhoods representing four points on the rural to urban continuum, in a study area in Franklin County Ohio (including the City of Columbus).