FED UP WITH ENERGY HUNGRY AGRICULTURAL LANDSCAPES: USING ENERGY PRINCIPLES TO DEVELOP DESIGN GUIDELINES FOR AGRICULTURAL LANDSCAPES TO REDUCE ENERGY USE IN FOOD PRODUCTION

by

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(Under the Direction of Alfred Vick)

ABSTRACT

The 2014 world population is over seven billion and growing rapidly. Food production to feed this population relies on dwindling supplies of subsidized fossil energy. Experts agree that the potential of renewable energy is minimal and inadequate when compared to current global fossil energy use. The goal of this research is to aid in the transition to a post-industrial world by providing simple, effective ways to design productive farms by applying the laws of thermodynamics. The research question is: "How can the laws of thermodynamics influence landscape design and reduce direct and indirect energy inputs in rural agricultural systems to achieve energy independence?" Through a review of the energy laws, an analysis of modern agriculture, classification of agricultural inputs, and historical precedent studies, this thesis develops energy-based design guidelines intended to reduce the energy required for food production in order to foster a safer, healthier and more secure future.

INDEX WORDS: energy, agriculture, sustainable agriculture, agroecology, organic agriculture, energy landscapes, energy-based design, design guidelines

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DEDICATION

To all those who inherit what we leave behind.

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This thesis is a result of two teachers who challenged me to think beyond the classroom material and understand how the subjects (natural resources and energy) affect every single one of us in every way. They taught me to never stop problem-solving and to look deeper than just the science or the politics or the social issues, and attempt to grasp the entirety of the problems I encounter. I want to thank Dr. David Gattie and Dr. John Schramski for all that they have taught me and the many questions—some thoughtless and some thoughtful—that they have answered. I've been blessed to have them both as professors, and I hope they keep doing what they are doing. They are changing the world.

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CHAPTER 1

ENERGY AND THE FOOD SUPPLY

Up until the past few centuries, humans harvested their energy from phytomass. It wasn't until the British began mining coal in the 1600s that the dense stores of ancient solar energy known as fossil fuels were first exploited (Stremke and van den Dobbelsteen 2013). This solar energy that was long ago captured by biomass was eventually, through slow heat and pressure transformations, made into a high quality fuel, which is now extracted as coal, oil, and natural gas. Formation of the high quality stores of energy began approximately 50-350 million years ago, giving them the name "fossil" fuels. Even now, fossil fuels are steadily being formed, though the rate of consumption greatly exceeds the rate of creation (Smil 2008). Therefore, fossil fuel reserves are now being depleted. As scientist Frederick Soddy said in 1912 regarding the difference in utilizing fossil fuels instead of natural energy flows, "The one is like spending the interest on a legacy, and the other is like spending the legacy itself" (Smil 2008, 8). In an effort to reverse the trend, the search for renewable replacements is growing, yet proving to be a huge challenge. The energy density of the replacements—wind, solar, water, and biomass—is much lower than that of the fossil fuels, and therefore much larger areas are required to harvest a comparable amount of energy (Stremke and van den Dobbelsteen 2013, MacKay 2009). Currently, the consumption of fossil energy is so great that the amount being consumed is greater than the amount of energy that can be feasibly renewably harvested (MacKay 2009). To live off of renewables we must drastically cut our energy consumption and increase efficiencies (MacKay 2009). Increasing efficiencies is usually assumed to be through new technologies, but efficiency can result from smart land planning and design that takes into account the laws of thermodynamics as well. Another obstacle is the natural resource base (i.e. materials) required to build the technology to harvest the energy. The earth has a finite amount of resources and a growing human population.

<u>Feeding the World</u>

In the United States, an estimated 19% of the fossil energy consumed is used in food production (Pimentel and Pimentel 2008). This may not seem like a large percentage until put into perspective—it is more than twice the total per capita fossil energy consumption in Asia and approximately four times that in Africa. To think of it another way, Pimentel and Pimentel (2008) ask: If U.S. agricultural technologies were used to produce all the food to feed a stabilized global population of 5.5 billion people a high protein/calorie diet, how long would it take to deplete the known oil reserves of petroleum? The known oil reserves are estimated to be $90x10^{12}$ L. Making the assumptions that 75% of the crude oil can be converted into fuel, oil were the only source of energy used for food production, and that all the reserves were used for only food production, $67x10^{12}$ L of oil remains for food production. The oil to feed the world would only last for 7 years. Yes, that is making the assumption that oil is the only fossil energy being utilized. However, this is also assuming the global population is only 5.5 billion, when actually over 7.1 billion people currently inhabit the earth (United States Census Bureau, "U.S. and World Population Clock" 2013) and each day there are a quarter of a million more mouths to feed (Pimentel and Pimentel 2008).

How realistic is the above example? In 1865, economist William Stanley Jevons performed a calculation to answer how much longer British coal would last. Other people doing the same calculation would estimate the coal remaining by the rate of coal consumption at that particular time and get answers like, "1000 years." Jevons recognized that consumption is not constant, but instead had doubled every 20 years, and "progress" would require that trend to continue. Amory Lovins reinforces this exponential consumption noting, "Humanity has already withdrawn about one-third of the original fossil-fuel bank balance, and those once-in-a-civilization withdrawals are accelerating: half their total has occurred just since 1985" (Reinventing Fire 2011, 7). Jevons understood this acceleration and therefore calculated the time the total amount consumed would exceed reserves by extrapolating the exponentially growing consumption. He then projected that finite reserves of British coal would halt progress within 100 years. He was correct. British coal peaked in 1910, and by 1965 Britain was no longer a world superpower. The point Jevons made is that growth is not sustainable. Repeating this calculation for global coal reserves, which are estimated at 1600 gigatons (Gt), and using the 2% growth rate from 1930 to 2000, the end of coal would come in the year 2096. If the growth rate from the past decade (1999-2009) is used, the year is 2072 is projected as the end of coal (MacKay 2009).

Additionally, Shafiee and Topal (2009) developed a model to estimate the end of the fossil fueled era. In 2009, their calculations for the depletion of oil, coal, and gas are approximately 35, 107, and 37 years, respectively. That would mean oil depletion occurs around 2044, coal around 2116, and gas around 2046. Smil (2008) argues that the stocks of fossil fuels should not be viewed within a rigid frame due to all the factors in play: supply and demand and price changes, input costs, technological advances in exploratory, as well as production, distribution, and conversion techniques. A critical issue here is that the energy required for extraction increases as our reserves dwindle and become harder to reach. McKelvey's Box (shown in Figure 1.1) graphically demonstrates the reserves, which is proved possible and recoverable, in comparison to the resources, which are speculative and nearly impractical to extract, if they do exist (Smil 2008). The reserves are estimated to be 30 ZJ and the resources are the 200 ZJ.

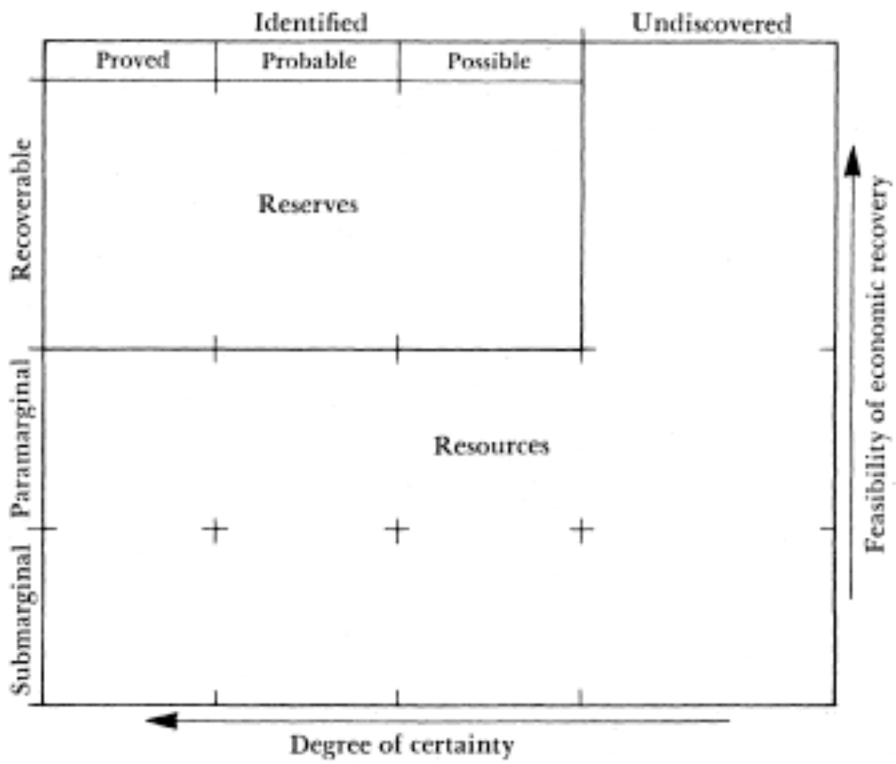

Figure 1.1: McKelvey's Box. McKelvey's Box is the standard U.S. classification system of nonrenewable mineral reserves. McKelvey's Box shows the degree of certainty of fossil fuels, decreasing from left to right, and the feasibility of recovery, decreasing from top to bottom (McKelvey 1972, 35).

However, the crisis will not culminate with the end of oil, as physicist David Goodstein predicts, "the crisis will bite, not when the last drop of oil is extracted, but when oil extraction can't meet demand" (MacKay 2009, 2). Canadian scientist, Vaclav Smil (2008) explains, “Exhaustion is then not a matter of actual physical depletion but rather a burden of persistent and eventually insupportable real cost increases resulting in declining availability of a resource” (205). Smil (2008) points out that “even the best efficiencies and the utmost conservation measures cannot extend their [fossil fuels’] life beyond several hundred years,” also noting that energetically, modern economies are inherently unsustainable (204). Still, we are trying to solve population and economic growth—the culprit of major global problems such as environmental destruction, poverty, unemployment, resource depletion, and urban deterioration—with more growth (Jackson 2010).

Given the oil predictions above and the energy intensity of U.S. agriculture, it may seem that information should be flowing from those who produce food without fossil fuels—perhaps in less industrialized countries—to those who are currently dependent on them. Instead, it often seems that the reverse is occurring, with U.S. food aid subsidizing a growing population beyond our borders. Meanwhile, the U.S. and other industrialized countries are pouring much of their resources into finding “less bad” ways to produce (McDonough and Braungart 2002, 60-62). Howard T. Odum writes in his book *Environment, Power, and Society* (2007), “Yet if fossil and nuclear fuels were cut off, we would have to find people still farming in older ways to show the currently affluent citizens how to survive on the land while the population was being reduced to make it possible” (190). In the meantime, the U.S. enjoys a very high quality of life, which few U.S. citizens are willing to relinquish—the basis of our problem. Our current way of life is supported by cheap fossil fuels and a fossil-based economy (Lovins 2011). Our luxuries are the products; for many, what we eat is consumed thoughtlessly, and there is a great disconnection between people and the land (Berry 1977). Wendell Berry argues that our “progress” in agriculture has fostered this disconnect and resulted in destruction of our land and our culture. In

The Unsettling of America, he points out that agriculture has its root in the word *culture*, and that the two are inextricable. The perversion of either, results in a perversion of the other. Berry argues the issue is "a crisis of culture" (Berry 1977, 38). Therefore, it is impossible to talk about the problems of agriculture and the energy consumption in U.S. agriculture without addressing the *culture* that each exists within. And we have become a wasteful culture.

In America, we waste 40% of our food (Gunders 2012). That means essentially 40% of the fossil fuel burned and 40% of the land degradation from agriculture is unnecessary. We also purchase "goods" that quickly become "clutter" then "rubbish" (MacKay 2009, 88), while people all over the globe are living in hunger. Evidence suggests that the current agricultural system is neither meeting the needs of a global population nor sustaining a healthy global ecosystem. Difficult choices will need to be made and significant changes in lifestyles and agriculture, or both, are likely. Yet, the popular "green" movement is not about necessarily changing lifestyles or sacrificing, but being "less bad." The intentions are good, but the science behind it is often lacking (McDonough and Braungart 2002).

An example of trying to be "less bad" and having good intentions of "sustainably" feeding the world is seen in *The Top 100 Questions of Importance to the Future of Global Agriculture*, published by the International Journal of Agricultural Sustainability. Pretty et al. (2010) pose questions such as "What are the best options for agriculture increasing food production while simultaneously reducing its contribution to greenhouse gas emissions?" and "How can competing demands on land for production of food and energy be best balanced to ensure the provision of ecosystem services while maintaining adequate yields and prices?" or "As energy prices rise, how can agriculture increase its efficiency and use fewer inputs and fertilizers to become economically sustainable and environmentally sensitive, yet still feed a growing population?" (225, 232). But, are we asking the right questions? As Joel Salatin points out in his book *Salad Bar Beef* (1995), "The ability to solve problems is directly related to the questions we ask… our questions define the bounds of our problem-solving. And generally, our paradigm defines what we perceive as a problem" (16).

These questions are based on the assumption that the carrying capacity of the earth is 9 billion people. Odum comments on the issue of human population in *Environment, Power, and Society* writing, "When resources are not limiting, systems grow… at least for a while" (Odum 2007, 46). The Industrial Revolution unleashed what seemed to be an unlimited source of energy, so energy was no longer limiting. Later, energy was employed to manufacture synthetic nitrogen fertilizer for crop growth, and nitrogen was no longer a limiting factor for those who could afford it. This allowed for a population explosion (i.e. the growth of a system). Odum (2007) asks, "When energy supplies support accelerating growth, users with faster growth rates outgrow and displace others" (46). This is evident in the growth of the human population and our displacement of other species in the ecosystem. Furthermore, fossil energy provides a "short-circuit" according to Odum (2007),

> "If we arrange for a flow of concentrated energy to disperse the energy directly into the environment, the heat releases will become so concentrated that localized heat gradients will develop to do work while the energy is dissipating…. A related example is found in human populations, when support is being provided without work being required in return. If an idle population does not have to engage in a regular work process, it tends to set up various unorganized activities. If no organized outlet for human contributions is arranged, unrest, mob actions, irresponsible reproduction, and social eddies can result, at least until a new closed loop system evolves by selection" (58).

This short-circuit brings us to present-day—over 7 billion people on the planet, 842 million of whom are malnourished (Food and Agriculture Organization, "The State of Food Security in the World 2013" 2014), with the population increasing by a quarter of a million more people everyday, and a finite amount of fossil fuels to support them all. In 2013, the U.S. population was approximately 317,000,000 (United States Census Bureau, "U.S. and World Population Clock" 2013), of which 101,750,000 were unemployed or not in the labor force, 143,929,000 were employed, totaling the civilian noninstitutional population[1] of 245,679,000 (United States Department of Labor, "Labor Force Statistics from the Current Population Survey: Employment status of the civilian noninstitutional population, 1943 to date" 2014). These numbers leave approximately 71,321,000 U.S. citizens unaccounted for.

The amount of people who do not work today is vastly different than that in early hunting and gathering societies, where every member was needed to contribute to food security, and minimal energy was left to devote to societal structure. Over time, developments in agriculture led to less energy (i.e. people) required for food production to feed the society. This excess energy from the surplus allowed for the specialization of nonfarmers. Eventually, developments and technologies provided a reliable food supply, and populations began to grow. People concentrated in cities and towns, and labor became more specialized, and societies developed more structure (Pimentel and Pimentel 2008). These societies were becoming industrialized due to newly discovered available energy. With the excess of energy that fossil fuels provide, Odum (2007) notes the social "eddies" that may result, including irresponsible reproduction leading to a booming population. Odum writes,

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[1] The civilian nonstitutional population, as defined by the Bureau of Labor Statistics, "consists of persons 16 years of age and older residing in the 50 States and the District of Columbia who are

"The biggest cancer of them all is the human population itself. Removed from its normal controls by modern medicine, global population has accelerated past 6 billion. Using fossil fuel, some human populations have gone into a mode of competitive exclusion, consuming resources, setting up subcompetitions in their cultures and races, and generally draining the operating capital of the world toward its collapse" (58).

Ultimately, the laws of thermodynamics are what govern our existence on planet Earth, though this may seem barbaric to a modern civilization enjoying the luxuries of a growing fossil-fueled economy, being guided by a political system with its own set of laws. Odum (2007) acknowledges this saying, "Ignorance about energy develops during times of accelerating growth" (57).

Wendell Berry (1977) acknowledges the growing population, but states outright,

"We must, I think, be prepared to see, and to stand by, the truth: that the land should not be destroyed for any reason, not even for any apparently good reason. We must be prepared to say that enough food, year after year, is possible only for a limited number of people, and that this possibility can be preserved only by the steadfast, knowledgeable care of those people" (10).

Therefore, even seemingly helpful programs and practices with good intentions will, Berry goes on to write, "in the long run, cause more starvation than they can remedy" (Berry 1977, 10).

McDonough and Braungart comment on this "eco-efficiency" that does not truly address the root of the problem, just aims to treat it, and they note eco-efficiency may actually be worse, because an ecosystem may actually have a chance to recover after a quick collapse that leaves some niches intact versus a "slow, deliberate, and efficient destruction of the whole" (McDonough and Braungart 2002, 62-3). These authors are calling for a transformational redesign of the way we make things, or in the case of agriculture, how we grow things. Yet, with modern agriculture a fundamental part of our economy and security in the world, it would be absurd to suggest switching over to a truly sustainable agriculture tomorrow, though a complete transformation is needed—not just a "less bad" way. This is an environmental and ethical imperative if we are to leave an environment and natural resource base sufficient for meeting the needs of future generations.

By addressing energy, we can address the whole system (J.R. Schramski, submitted for publication, personal communication) and the root of the problem. After all, many of the identified problems of modern agriculture, discussed in Chapter Three, have developed since fossil-fueled tractors started appearing on farms around 1910-1920 (Smil 2008). Soil erosion is one example. Cornell scientists wrote in 1995, "Soil erosion is a major environmental threat to sustainability and productive capacity of agriculture. During the last 40 years, nearly one-third of the world's arable land has been lost by erosion and continues to be lost at a rate of more than 10 million hectares per year" (Pimentel et al. 1995, 1117). By 1955, a decade after World War II, industrial agriculture was really ramping up—more tractors were on more farms than ever before.

Climate change is another glaring example of how addressing energy addresses the whole system. Millions of research dollars are being spent on finding ways to cope with climate change, many by using more technology and more fossil energy. Yet, fossil energy is the main contributor. Smil (2008) regards the combustion of fossil fuels and land use changes as the main sources in the interference of our global cycle (328). This is not to say that humans cannot do great ecological damage without fossil fuels—England's pre-Industrial Revolution deforestation is an example (Smil 2008). For true sustainability, deforestation must also be addressed—and deforestation is a lot more difficult without subsidized fossil energy, at least on a massive scale. However, as a measure of sustainability, energy balance could be a measure that addresses the root of many problems (J.R. Schramski, personal communication). This balance can begin on farms—in the soil, in the fields, and over the landscape. Despite the controversial projections on when we have to "switch over," the time to start is now. We may start at a small scale or by implementing incremental measures to initiate change, but eventually, transformational measures will be required to balance our global energy budget.

Many wonder and many debate when fossil fuel reserves will diminish. It is not the purpose of this research to answer that question, but following the above discussion, most will conclude that to depend on a finite source of energy for food production is not a secure or stable approach for any civilization. Additionally, all would agree that food is a basic need for life. Therefore, it is of the utmost importance that agricultural systems be designed to function and operate without fossil energy. These numbers are merely presented to impress the need to become energy independent.

The point of this research is to prepare landscape architects and farmers for the inevitable transition from fossil fuels by providing simple, low-cost ways to design and manage the land that will be effective and productive by applying the laws of thermodynamics, reinforced by historical precedents, to the design of agricultural systems. These methods will ultimately cut input costs. As the price of oil has risen in the past several years, so has the price of fertilizer and feed. With demand growing and supplies dwindling, it is obvious that food production dependent on these products will not remain profitable or either affordable, and that this current system cannot endure beyond the next 30 to 40 years. Some methods may be similar to the way things were done before the industrial agricultural revolution, but pressure to produce will be much greater, as the population since James Watt invented his steam engine in 1769 has grown by over 6 billion (MacKay 2009), and society now has the knowledge that 250 years of industrialism and fossil fuel technology has allowed.

Thesis Structure

This thesis asserts that the design of rural agricultural landscapes can reduce and ultimately eliminate nonrenewable fossil fuel energy consumption on farms, allowing them to persist in the way that self-regulating ecosystems abide, with an energy return on energy invested (EROI) of greater than or equal to one. Understanding the importance of reducing our fossil fuel dependence, this thesis asks: How can the laws of thermodynamics influence landscape design and reduce direct and indirect energy inputs in rural agricultural systems to achieve energy-independence?

The purpose of exploring this question is to address ways that landscape architects can contribute our knowledge and skills to working with others and creating solutions that address the security of one of our most basic needs—food—while managing an environment that will be healthy enough to produce for generations to come and designing in such a way that we will not be dependent on finite fossil fuels to produce our food.

The goal of this thesis is to inform landscape architects, farmers, scientists, politicians, and economists, among others, of the energy challenges that face us, and to encourage us to begin thinking within the laws of nature that we must live within, and how to take simple incremental steps toward natural resource conservation measures to ensure a safe, adaptive, perpetuating food production system. This is a complex subject socially, economically, and environmentally, and no certain answers exist yet, and the issues are constantly evolving. In consideration of the situation, this thesis will focus on the laws of nature, the boundaries they create, and how systems can be designed to operate within these boundaries.

This research is limited by its generalizations. The focus is on integrated whole systems that abide by energy principles to reduce energy needs. Though details and site-specific design and management are essential, this thesis aims to approach the design of agricultural systems with whole systems thinking to capitalize on complex energy flows, symbiotic relationships and trophic level interactions in order to survive long-term without fossil fuels. As Wendell Berry (1977) points out, "the land is too various in its kinds, climates, conditions, declivities, aspects, and histories to conform to any generalized understanding or to prosper under generalized treatment," (31). Machinery and brute force have contributed to the general treatment of land, but understanding the land and its ecological principles can help relieve the need for this brute force and the fossil fuels that feed it. The laws of thermodynamics and the basic relationship between plants and animals are constant—and the design guidelines will address the design of the resource flows and balance of the system as they relate to energy needs. In addition, the ongoing management of the land ultimately determines the reliance on fossil fuels. The management is also beyond the scope of this research, but the design guidelines will lay the foundation for fossil fuel independent management to follow. Lastly, this research is limited in its ability to practically be implemented immediately. The challenges that face humanity are the result of subsidized (i.e. fossil) energy use, and we need the excess energy to transition back into a society that can again live within our energetic means.

In order to address the research question, the following sub-questions must be answered:

1. What are the laws of energy and how are they evident in ecosystems?

2. How is energy currently used in agriculture, what are the inputs and why are they needed?
3. How were the laws of energy applied to agriculture in the past before fossil energy became widely used?

Chapter One discusses the current relationship between food supply and energy and introduces the thesis structure. Chapter Two explores the laws of energy, biological and fossil energy, and the current state of renewable energy for the future. Sub-question two is addressed in Chapter Three in order to better understand how modern agriculture currently uses energy. Chapter Four explores the role of energy in agriculture, historically and at present, and the change of lifestyles and population densities. The energy-based design guidelines for regenerative, fossil energy-dependent agricultural landscapes developed from this research are presented in Chapter Five. Following the guidelines, Chapter Five ends with an analysis of the energy-based design guidelines, as well as concluding thoughts regarding fossil energy-independent agricultural landscapes.

CHAPTER 2

ENERGY

To understand how the laws of energy can be applied to agricultural landscapes, energy and its role in society should first be explained. After a discussion of the energetic basis of social phenomena, the classic energy laws and a few important energy concepts are introduced. Next, the principle of energy hierarchy is explained, followed by a discussion of biological and mechanical energy, an overview of energy analyses, and a discussion of renewables. Finally, our energy problem is related to our altered atmosphere and ecosystems at the end of this chapter.

What is Energy?

In the textbook *Thermodynamics: An Engineering Approach*, energy is defined as the ability to cause changes (Çengel and Boles, 2). Yet often energy is explained as the capacity to perform work; Smil argues, however, that this definition is too reductionist in its mechanical connation and defines energy as the ability to transform a system (12-13). The process of transforming a system can involve any kind of energy, and there are many types including thermal, mechanical, electrical, chemical, and nuclear. Table 2.1 lists the many types of energy and their conversion methods.

Table 2.1. Types of Energy Conversions (Smil 2008,14).

to \ from	electro-magnetic	chemical	thermal	kinetic	electrical	nuclear	gravitational
electro-magnetic		chemi-luminescence	thermal radiation	accelerating charge phosphor	electro-magnetic radiation electro-luminescence	gamma reactions nuclear bombs	
chemical	photo-synthesis photo-chemistry	chemical processing	boiling dissociation	dissociation by radiolysis	electrolysis	radiation catalysis ionization	
thermal	solar absorption	combustion	heat exchange	friction	resistance heating	fission fusion	
kinetic	radiometers	metabolism muscles	thermal expansion internal combustion	gears	electric motors electro-strictions	radioactivity nuclear bombs	falling objects
electrical	solar cells photo-electricity	fuel cells batteries	thermo-electricity thermionics	conventional generators		nuclear batteries	
nuclear	gama-neutron reactions						
gravitational				rising objects			

Still, energy seems abstract. Everyday phenomena have their energetic origin in the sun's thermonuclear reactions, from a baby crying to lightning and rotating steam turbines (Smil 2008). Energy is everywhere. Wilhelm Ostwald, a German chemist with a Nobel Prize in chemistry, wrote in his 1892 *Fundamentals of General Energetics*,

"The concepts that find application in all branches of science involving measurement are space, time, and energy. The significance of the first two has been accepted without

> question since the time of Kant. That energy deserves a place beside them follows from the fact that because of the laws of its transformation and its quantitative conservation it makes possible a measurable relation between all domains of natural phenomena. Its exclusive right to rank along space and time is founded on the fact that, besides energy, no other general concept finds application in all domains of science. Whereas we look upon time as unconditionally flowing and space as unconditionally at rest, we find energy appearing in both states. In the last analysis everything that happens is nothing but changes in energy" (Lindsay 1976, 339).

Energy is everywhere. The biggest source is the sun. Incoming, high quality solar radiation is the energy that fosters photosynthesis in plants. Though fossil energy is very important to U.S. agriculture presently, the system ultimately relies on solar energy for plant growth. Plants, in turn, feed animals, allowing them to grow, eventually becoming farm products. (The section *Biological and Fossil Energy* expands more on this.) Solar energy is also fundamental to wind, hydroelectric, tidal, and other forms of renewable energies (Pimentel and Pimentel 2008). Such things as biomass (i.e. wood), gasoline, and wind are not energy—they are energy currencies. Energy is intangible and it comes in different qualities and different quantities.

For measuring quantities of energy, the joule (J) is the basic unit of energy in the International System (SI). Energy is often measured with other units such as the calorie, British thermal unit (Btu), or kilowatt-hour (kWh). The joule is equivalent to a newton-meter (Nm), a force times a distance—a simple way to measure work (Çengel and Boles 2006). Work requires the use of energy at a certain rate. The rate at which work is done is referred to as "power." The basic unit of power is the watt (W); the watt the equivalent to 1 joule/s. Horsepower (HP) is another unit of power, and 1 HP equals 746 W or 2542 Btu/h. The rate at which work is done multiplied by the time required for the work is equal to the total energy flow. Also, power density is another common term. Power density is the flow of energy per unit area per unit time, or simply the power per unit area (Odum 2007).

Depending on the scale, different orders of magnitude may be used to measure energy—kilojoules (kJ), megajoules (MJ), gigajoules (GJ), terajoules (TJ), or zettajoules (ZJ). A kilojoule is equal to $1x10^3$ joules, a megajoule is equal to $1x10^6$ joules, a gigajoule is equal to $1x10^9$ joules, a terajoule is equal to $1x10^{12}$ joules, and a zettajoule is equal to $1x10^{21}$ joules.

To put these units in perspective, compare the power of a person, a horse, and one gallon of gasoline. The maximum work capacity of power level sustained by one horse over a 10-hour work day is 1 HP. The power level of a person is about one-tenth of 1 HP, therefore a 10-h day results in a total flow of energy equivalent to 1HPh (horsepower hour), or 2.7 MJ. This means one horse can do the same amount of work as 10 people in one hour. Now compare this human power to the mechanical power achieved by a tractor fueled with one gallon of gasoline. One gallon of gas contains approximately 31,000 kilocalories (kcal) of potential energy, which can be converted into heat energy then mechanical energy in a mechanical engine with about 20% efficiency. The result is 8.8 kWh, 11.8 HPh of work. This means that one gallon of gas can produce more power than a horse working for 10 hours at maximum capacity (7.5 kWh) or one human working for three 40-h weeks at the rate of 0.1 HP (Pimentel and Pimentel 2007, 12). Gasoline is a very dense, high quality form of energy. Understanding the comparatively huge amount of energy in one gallon of gasoline explains how the discovery of fossil fuels forever changed society.

Energy and Society

The sun emits solar radiation, and before the Industrial Revolution, all societies derived their energy from almost immediate transformations of solar radiation (Smil 2008). The internal heat and gravitational forces of the earth are the other two most significant sources of energy for our planet. These sources are essential for life, but contribute much less quantitatively to the energetics of the earth (Smil 2008). Until the Industrial Revolution began in the Western world, there existed four types of energy that preindustrial societies employed: human and animal labor, flowing water, wind, and biomass (Smil 2008). Most of the energy in preindustrial societies was spent on obtaining food, which will be covered more in Chapter Four. These civilizations primarily harvested energy from the earth in the form of biomass.

As these preindustrial civilizations were (renewably) using biomass for energy over many millennia, fossilized stores of solar energy formed in the earth's crust. These stores are dense packages of energy. As England and France were expanding their ship fleet and building homes for the growing population in the1500s, they began running out of biomass. Wood was harvested for cooking, construction, and charcoal for the growing metal industry. Deforestation occurred, and a new source of energy was needed. At this point, coal began to be harvested from the earth for fuel. Initially, it was used mainly for heating. But by the 1800s, civilization had replaced human and animate energy with the newly discovered fossil energy (Pimentel and Pimentel 2008). In addition to fossil energy, by 1880, modern civilization had discovered a second kind of energy. This type of energy did not require the user to be near the source because it could be distributed over distances. In 1882, it lit 5,000 street lamps in New York City, and today fossil fuels produce 60% of what we know as electricity (Smil 2008).

Fossil energy is mined as coals and hydrocarbons (i.e. crude oils and natural gases), and is often burned to generate electricity. Electricity is also generated using nuclear fission, water, and wind (Smil 2008). Some of these methods for producing electricity are becoming more popular as people search for sources of renewable energy with the goals of reducing carbon footprints and/or becoming more "sustainable."

These new forms of energy allowed for an explosion in population. As mentioned in Chapter One, the global population has increased by over 6 billion people since James Watt's 1769 invention of the steam engine—the often-recognized beginning of the Industrial Revolution. In order to grow food and build homes and provide services for our 7.1 billion people on earth, land is continually being cleared, and, inevitably, biomass is being lost. With a population projection of 9 billion by 2044 (United States Census Bureau, "International Data Base World Population: 1950-2050" 2012), the trend in deforestation is not likely to change any time soon, and in addition, we will have a decreased ability to produce food due to the current land-destructing agricultural practices (Berry 1977; Pimentel et al. 1995). With a population of just over 1.6 billion in 1900 (Smil 2000), the world had 23 ZJ of bioenergy potential, but by 2000, the bioenergy potential was reduced to 18 ZJ (J.R. Schramski, submitted for publication, personal communication). This decline in biomass stores affects the functionality of the planet through albedo increases and alteration the global carbon cycle (Smil 2008).

Additionally, the global net primary production[2] (NPP) is being impacted. The NPP is the amount of phytomass that may be renewably harvested each year; in economic terms, it is the interest, not the principal. The global NPP has decreased from 3.5 ZJ in 1900 to 1.8 ZJ in 2000.

[2] The global net primary production (NPP) is a measure of the amount of phytomass (carbon, energy) fixed in a year by photoautotrophs reduced by the energy the photoautotrophs require to produce the phytomass.

This means humanity has reduced the annual renewable potential of phytomass by nearly 2 ZJ in 100 years through deforestation, expansion of agricultural land, and land development. In terms of energy, the NPP represents the solar energy that is transformed via photosynthesis into plant material (i.e. phytomass) that is available to be renewably harvested each year. It is the only major sustainable energy gradient that exists for the animal kingdom to harvest energy from year after year (Schramski 2013, "Chapter 6: The Development of Agriculture"). Once an amount larger than the NPP is harvested, humanity is living beyond our means. We are spending the principal. In Figure 2.1, Schramski (citing Bazilevich and Rodin 1971; Smil 2013; Smil 2011; Smil 2008) compares the bioenergy potential and NPP in 1900 and 2000 and shows the remaining global nuclear and fossil fuel potential (submitted for publication, personal communication).

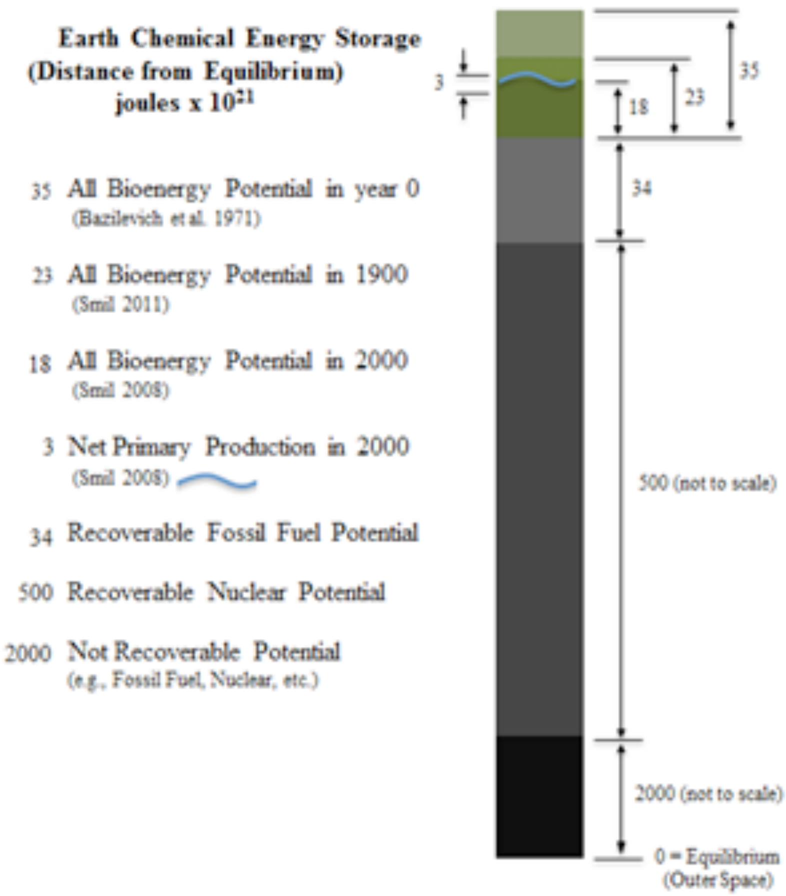

Figure 2.1. The Bioenergy Potential of the Earth, 1900 and 2000 (Schramski, submitted for publication, personal communication).

In addition to consuming approximately half of the global biomass, industrialized societies have a fossil fueled energy addiction that is altering our atmospheric composition. MacKay (2009) notes world oil consumption to be 80 million barrels of oil per day, or assuming equal distribution among the global population, 23 kWh/day/person. Other types of fossil fuels (i.e. natural gas and coal) are also used and contribute to fossil energy consumption. However, global distribution is not equal. The average consumption of a typically affluent person[3] is

[3] The values that MacKay estimates for energy consumption are derived from analyzing activities, products, and consumption patterns (i.e. transportation, heating and cooling, lighting,

approximately 195 kWh/day/person, according to MacKay (2009). Americans consume more than their fair share at approximately 250 kWh/day/person. In 2008, fossil fuels accounted for 94% of the total fuel consumption in the U.S. (Pimentel and Pimentel 2008).

Of this total energy consumption in the U.S., 19% is used in food production (Pimentel and Pimentel 2008). Of that, 30% is devoted to the production of synthetic fertilizers (Pimentel and Wen 1990). Smil contributes industrial nitrogen fixation with supporting 3 billion of the 7 billion people on earth (Smil 2000). The accelerating production of synthetic nitrogen arguably helps feed the hungry, but again, Americans waste 40% of our food, and as Odum (2007) points out, removing natural controls and adding excess energy to a system allows for more energy to create social eddies (i.e. go toward irresponsible reproduction) (58). Odum (2007) writes, "the giveaway of support in human affairs can be an energy short-circuit" (58). This can be applied to food, as food is the direct source of energy for humans. When we remove natural controls, thereby increasing the amount of food we produce with fossil fuels through synthetic fertilizers and chemicals, we are effectively subsidizing the human population and requiring less work and human labor for the production of food to maintain that population. This is an untenable situation because lives are being subsidized by a resource that is running out. Though many agribusiness propagandists would argue, as has been the case since at least 1970, this reliance on nitrogen fertilizer is not offering freedom from hunger to the "underdeveloped two-thirds of the world," (Berry 1977, 59-66), but furthering our reliance on cheap and abundant fossil energy—in fact, enslaving us to fossil energy. Offering short-term support to feed more people is creating a short-circuit and subsidizing a growing population, not to mention the ecological degradation

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gadgets, food and farming, "stuff" such as drink containers, batteries, junk mail, hairdryers, etc., and public services including military defense and universities) of a "typical moderately-affluent person" in the developed world (MacKay 2009, 22).

that results from our use of energy, hindering our ability to provide in the future. This argument continues to be tied back to population, because when discussing food production, the population determines the demand—humans are the other half of the agricultural equation. Pimentel and Pimentel (2008) write, “when human numbers exceed the capacity of the world to sustain them, then a rapid deterioration of human existence will follow” and nature will ultimately control the human population (33-34).

However, this too follows the principles of energy hierarchy and pulsing. Odum (2007) points out that systems that go into competitive exclusion (i.e. humanity) grow and displace others (57), but that civilization itself is a “high-transformity, unsustainable pulse” (124). Like a pulse, there is a growth supported by consumption of energy and resources, followed by a successional reset (Odum 2007). Many experts use their models to show a gradual descent to a lower energy world, though most warn of apocalyptic crashes (Odum 2007). Energy principles, models and ecosystems show that either is possible (Odum 2007). Odum (2007) also warns that society needs to “succeed in changing attitudes and institutions for a harmonious descent” or either prepare information for a contingency restart after crashing (389).

This further explains the vital role of energy in society and food production and points out that humanity must understand and abide within the laws of energetics to adapt and persist indefinitely. This understanding lays the foundation for this research to expand on the principles of energetics pertaining to how they can influence the design of agricultural systems for energy-independence.

Energy Laws and Principles

Energy and some of its implications for society are briefly explained in the previous section. Before delving into how these laws can be applied to agricultural landscapes, the classic (first and second) laws of thermodynamics will be explained. Next, we will cover more energy terms including exergy, power, emergy and empower before discussing Odum's proposed fifth law of thermodynamics, including its application to spatial patterns, concentrating materials, information, time and storage, territory, turnover time and transformity, across scales, and in the landscape. [The third law or the fourth law, sometimes referred to as the zeroth law, will not be covered because these laws concern the thermal properties of systems and it is assumed that all landscapes are above absolute zero (i.e. 0°K) and abide by the fourth law regarding thermal equilibrium.]

Before continuing, here are the energy systems symbols from Odum (2007). These symbols appear in diagrams throughout this thesis, and Figure 2.2 is intended to help the reader understand energy systems language.

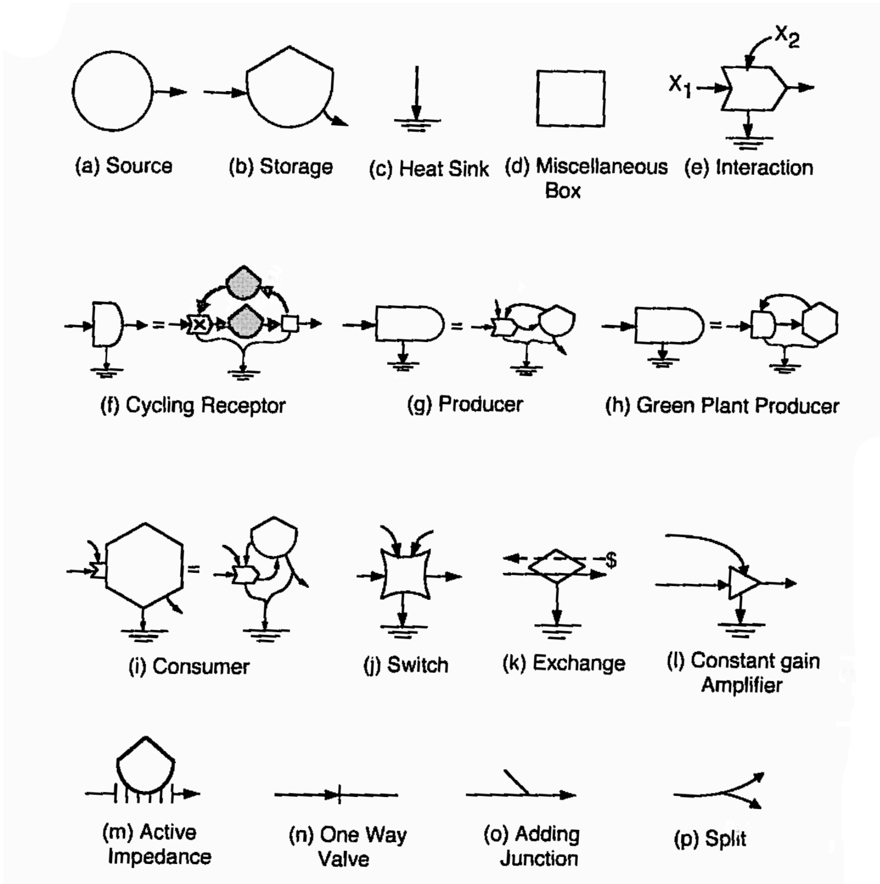

Figure 2.2. Energy Systems Symbols (Odum 2007, 26).

The First Law of Thermodynamics

The first law of thermodynamics, also known as the conservation of energy principle, states, "energy can be neither created or destroyed during a process; it can only change forms" (Çengel and Boles 2006, 70). Viewing the earth and its atmosphere as a closed system that is energized by solar radiation, gravity, and internal heat, the conservation of energy requires that the energy is balanced. Therefore, energy-in equals energy-out plus any chemical energy accumulation (i.e. biomass or fossil fuels) (Schramski, et al., 103). The incoming solar radiation is high quality, short-wave energy. The outgoing radiation is low quality, long-wave thermal energy. Earth has a constant source of incoming radiation from the sun, but what is not accumulated in the form of biomass is reduced to a low quality thermal radiation that exits the atmosphere, ensuring balance and satisfying the first law of thermodynamics (Schramski, "Chapter 2: Planetary Energetics"). For the purpose of explanation, the earth's atmosphere may be correlated with an adult human body and energy in the form of food. The high quality food-in must equal the low quality food-out plus any accumulation.

On earth, the energy accumulation occurs as biomass, and biomass is a source of energy for life. The accumulated biomass puts earth out of equilibrium with outer space, and being out of equilibrium is the requirement for harvesting or extracting energy. For example, a temperature and pressure differential is necessary for steam power plants to get work done—being out of equilibrium is a requirement. As seen in Figure 2.1, earth's biomass has decreased, bringing earth back closer to being in equilibrium with outer space and thereby lessening the ability of life on earth to get work done. The fossil fuel reserves on earth are also evidence of this balance, as the incoming solar energy has been stored in biomass made of carbon and transformed over long periods of time. Our fossil stores of old solar energy are now being harvested, and our gradient is decreasing. The first energy law holds true and energy is not destroyed or created, just transformed. These transformations are accounted for in the second energy law.

The Second Law of Thermodynamics

The first law of thermodynamics is concerned with quantity. The second law is concerned with quality. The second law of thermodynamics states, "no transformation of energy will occur unless energy is degraded from a concentrated form to a more dispersed form" (Pimentel and Pimentel, 9). Therefore, the second law requires that no transformation of energy is 100% efficient. This is realized in agriculture as crops convert solar energy to chemical energy for their growth, but not at 100% efficiency due to the heat energy that is lost in the process (Pimentel and Pimentel 2008). On average, plants are only 10% efficient at converting solar energy into ordered plant material of carbon and chemical energy (Pimentel and Pimentel 2008; Smil 2008). Because photosynthesis is only approximately 10% efficient, to get a highly ordered biomass, it takes a lot of input energy. Through the transformation, energy quantity is decreasing and entropy is increasing.

Entropy, a measure of the disorder in a closed system, relates to the second law of thermodynamics. Entropy measures available energy. Fossil fuels are high-quality (low entropy) forms of energy that are combusted to produce work, a valuable kinetic energy, and the transformation gives off heat—a low-quality (high entropy) form of energy. Therefore, not all of the energy is turned into work; some is transformed to heat and considered waste energy.

For example, gasoline is burned, a vehicle moves, and heat is produced, yet the process cannot be reversed; the heat of low-quality will never revert back to gasoline of high-quality; the process only goes in one direction satisfying the second law of thermodynamics. The first law of thermodynamics is also satisfied because the energy was transformed, not destroyed. The low quality heat energy then leaves the atmosphere. The work was paid for with the high-quality energy, and the result is an amount of work being done and thermal energy, which is useless due to its low quality.

Exergy

Whereas entropy measures the degree of disorder in a system, exergy is the available energy in a system. It is the amount of energy that can be extracted as useful work (Çengel and

Boles 2006, 424). Exergy recognizes the loss of quality from energy transformations, and is not conserved. In every transformation, exergy is destroyed because entropy increases.

Power

Power is not energy; power is the flow rate of useful energy (Odum 2007). Power measures the amount of energy transformed over a unit of time.

Lotka's Maximum Power Principle

The maximum power concept developed by Alfred Lotka in 1922 is important for understanding energy in ecosystems. Lotka reasoned that any species that finds a way to utilize excess energy would gain an advantage and would use that extra energy to grow in population. The population growth would then further increase the flux of energy through the system. In his 1925 book, *The Elements of Physical Biology*, Lotka recognized, "the problem of economy in husbanding resources will not rise to its full importance until the available resources are more completely tapped than they are today" (357). He also noted that every indication pointed to man learning to use the solar energy that goes to waste in order to "increase the rate of energy flux through the system of organic nature" (357-358). Odum and Odum (2001) interpret Lotka's concept of maximum power as, "In the self-organizational processes, systems develop those parts, processes, and relationships that capture the most energy and use it with the best efficiency possible without reducing power" (70). Systems then use this power for growth and maintenance (Smil 2008).

Autocatalytic Growth

Autocatalytic, or exponential, growth occurs in systems that use products of growth to help capture more energy in order to help them grow even faster. As Odum's figure shows, this is the situation when a sheep eats grass, grows, and maintains storage and growth by feeding on the grass. Alternatively, a city is also shown in Figure 2.3. The city generates hydroelectric power and uses it for growth in the town. The growth is put back into generating more power. One notable difference in these two examples is the waste from the growth. The sheep's waste returns to the soil to promote more grass growth through providing nutrients and organic matter, which in turn again supports the sheep. The waste from the town does not go back into capturing more power—it is waste.

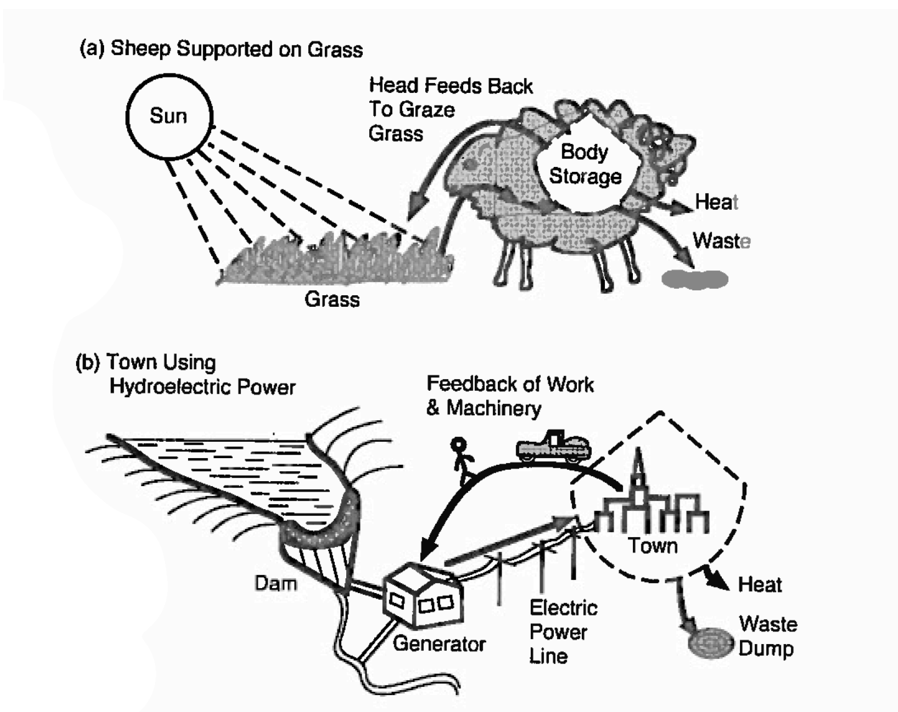

Figure 2.3. Examples of Autocatalytic Growth. (a) A sheep captures more energy. (b) a town captures more energy (Odum 2007, 47).

Emergy and Empower

Various types of energies differ in their abilities to do work. Solar radiation ultimately provides energy to grow the plants that make the coal to burn in a power plant, which generates the electricity to power a light bulb. The solar energy is different than the electric energy, as it took a lot of units of solar energy to create one unit of electric energy. The energy cascade (i.e. solar energy to chemical energy to thermal energy in the power plant to electrical energy) explained above is a series of transformations, of which the second energy law requires losses at each transformation. To compare the energies of different kinds at different steps in a transformation series and understand the total energy input or "embodied energy" for each, the energy needs to be expressed in units of the same kind (i.e. a calorie of sunlight is not equivalent to a calorie of electricity). To compare the two, Odum created a term called "emergy." Emergy is defined as "the available energy of one kind previously used up directly and indirectly to make a product or service" (Odum 2007, 68-69). Whereas many transformations must occur before the light bulb can be powered—"emergy carries the memory of the availability that was used up" (Odum 2007, 69). Solar emergy is often the measure, and it is often measured in solar emcalories (secal). Additionally, just as power is energy flow per unit time, empower is emergy flow per unit time (Odum 2007, 69). Figure 2.4 by Odum shows the transformation series from solar energy to vegetation to coal to electric power to lights.

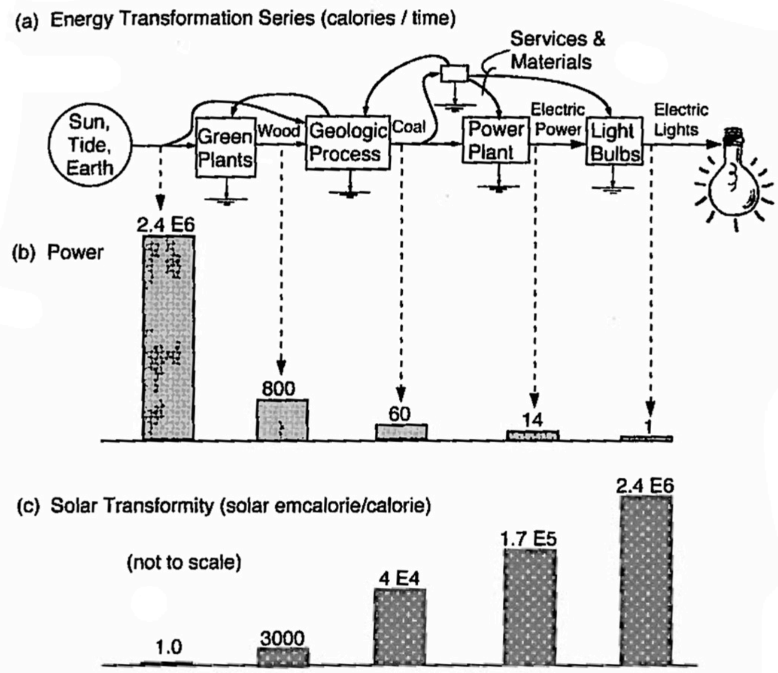

Figure 2.4. Energy Transformation (a) Energy Transformation Series from solar energy to electrical lighting; (b) Bar graph depicting power lost with each transformation; (c) Solar emcalorie required per calorie for each step in the transformation series (Odum 2007, 70).

Transformity

Odum defines transformity as "the calories of available energy of one form previously required directly and indirectly to generate one calorie of another form of energy" (73). Transformity is the emergy divided by energy or empower divided by power. Figure 2.4 (c) shows the solar transformity of electric lights to be 2.4 E6 solar emcalories/calorie. The transformity in this case is the calories of solar energy required to get to one calorie of electric light energy. Transformity can also be measured in emjoules/joule.

The Fifth Law of Thermodynamics - The Hierarchy of Energy

Energy hierarchy principles relate energy transformations between scales and account for "spatial organization and distribution of pulse intensity, stored quantities, and material concentrations" (Odum 2007, 63). These principles are evident across landscapes as energy transformations occur between trophic levels and as people interact with other people and resources. The second law focuses on one single transformation. Again, it requires that for each energy transformation, some energy be transformed into the output and some energy be dissipated as low quality heat energy (i.e. lost to the system for use). A flow of energy is evident from a systems perspective. The spatial relationships that result from these energy flows change depending on the incoming amount of energy. The spatial arrangement of agricultural landscapes can be manipulated to prepare for a decrease in input fossil energy, and in fact, can take advantage of natural energies to decrease the need for external fossil energy input. The next few paragraphs will explain energy hierarchy before relating it to spatial arrangements.

Energy transformations occurring in a series have a large quantity of energy inputs that go into creating an output that has less quantity but higher quality. Of the output energy, some continues on to the next transformation, while some goes back into the input process, interacting and controlling the input. Some is lost as heat energy (Odum 2007). Figure 2.5 shows a three-step transformation.

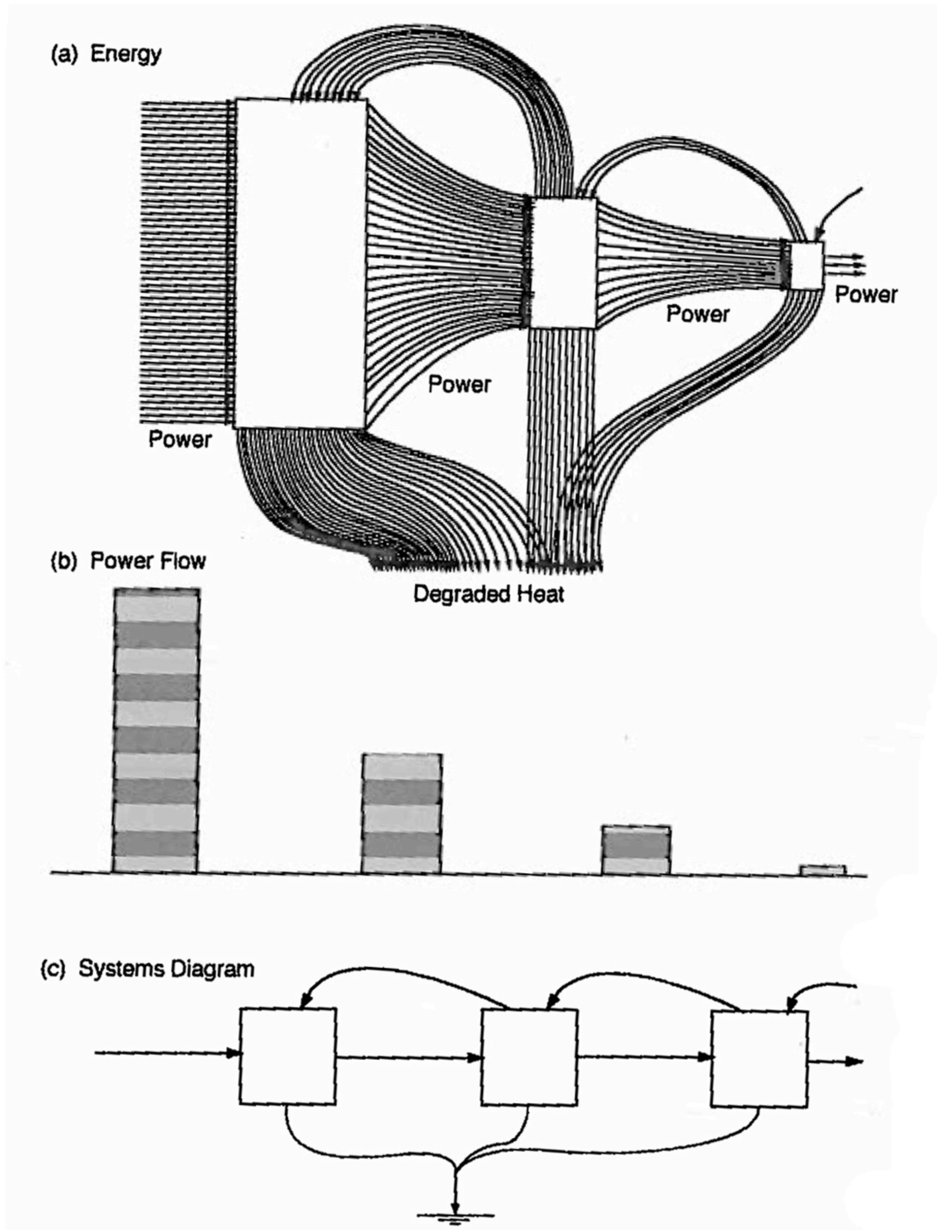

Figure 2.5. Energy Hierarchy of Flows and Transformations. (a) Power flows are shown through a transformation series. Each line represents a calorie of energy flow per time; (b) A bar graph represents the useful power output after each transformation corresponding to the energy flow visual above; (c) A systems diagram showing the energy flows (Odum 2007, 66).

Energy hierarchy, as depicted in Figure 2.5, is energy units of one kind combining to feed into another kind, which then feed back control. Energy flows decrease through each transformational step to the right (Odum 2007) until there is no available energy remaining. Odum gives an example of this to help readers visualize energy hierarchy. He correlates it to the hierarchical organization of an army in which many privates support a corporal, corporals support a sergeant, and many sergeants support a lieutenant, etc. Simultaneously, high-quality control feeds back from lieutenants to sergeants to corporals to privates (Odum 2007). Odum's example of energy hierarchy is shown in Figure 2.6. Odum (2007) proposed the universal hierarchical self-organization of energy systems be recognized as the fifth energy law (65).

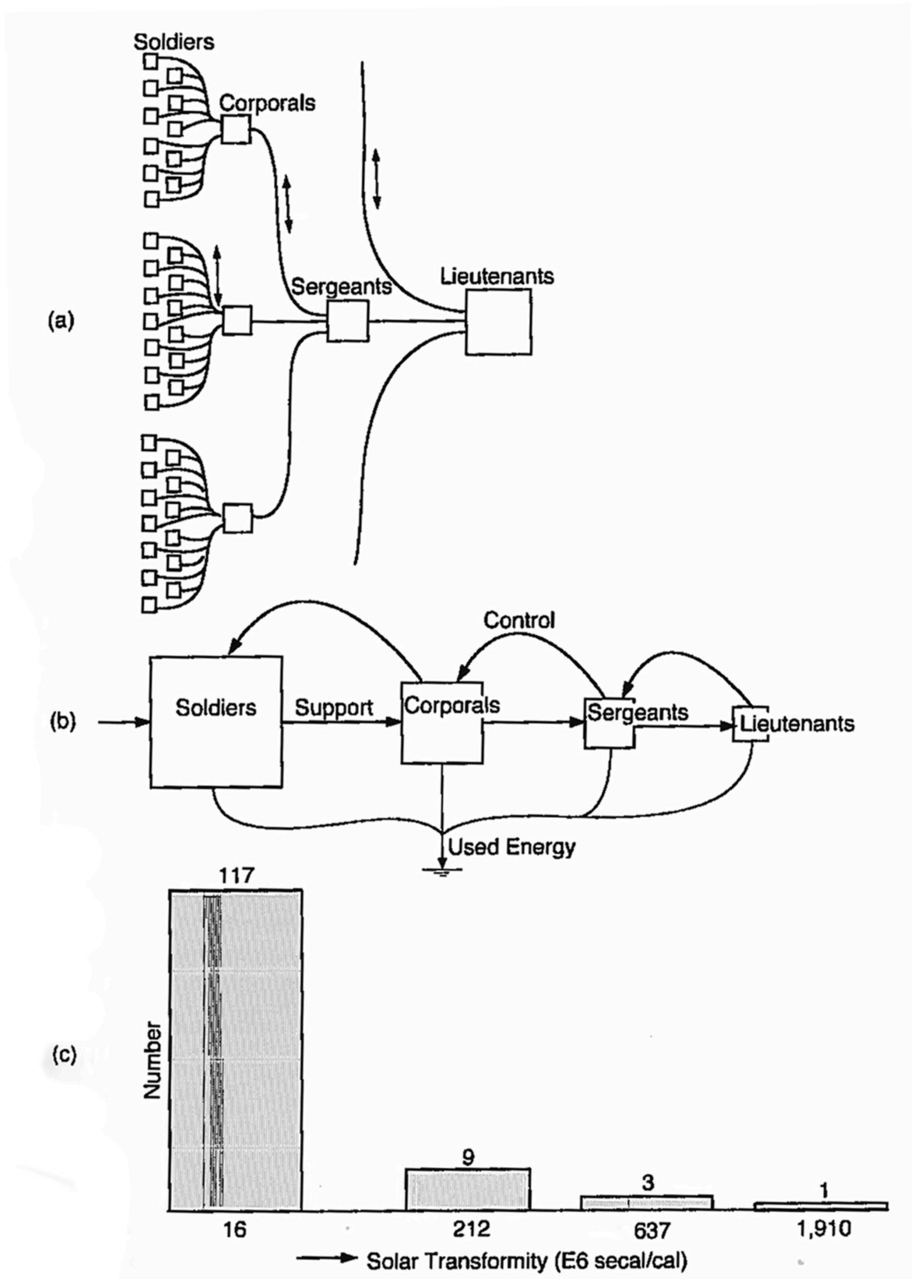

Figure 2.6. Energy Flows in the Military Hierarchy. (a) Military hierarchy schematic; (b) Energy systems diagram showing feed back controls; (c) Transformity units (Odum 2007, 67).

Spatial Patterns of Energy Hierarchy

Odum states, "the self-organization of energy into hierarchies explains how and why phenomena over the surface of the landscape form spatial centers of energy transformation on all scales" (Odum 2007, 76). Human settlement patterns are an example of how small centers converge their outputs to larger centers, which converge their output to even larger centers with the larger centers, in turn, supporting the smaller centers. The hierarchy of villages, towns, and cities is evidence of energy hierarchy. Similarly, Odum notes that ecologists see this relationship in trees, where the leaves support the energy for the branches, which feed back support for the leaves. The branches feed the trunks, which feed back to the branches. Other studies (Jarvis and Woldenburg 1984, Leopold and Langbein 1962) show this hierarchy occurring in watersheds with water self-organizing from smaller streams to larger streams eventually to rivers. By converging at these centers, flows are concentrated so the feed back control from the centers can have a strong effect by spreading useful work over the contributing area, helping to overcome the decrease in energy occurring with each transformation. Converging energies to centers helps maximize power (Odum 2007). Another important point is that to concentrate something or maintain its concentration, some available energy has to be used up in some transformation process (Odum 2007). Figure 2.7 depicts spatial patterns of energy hierarchy.

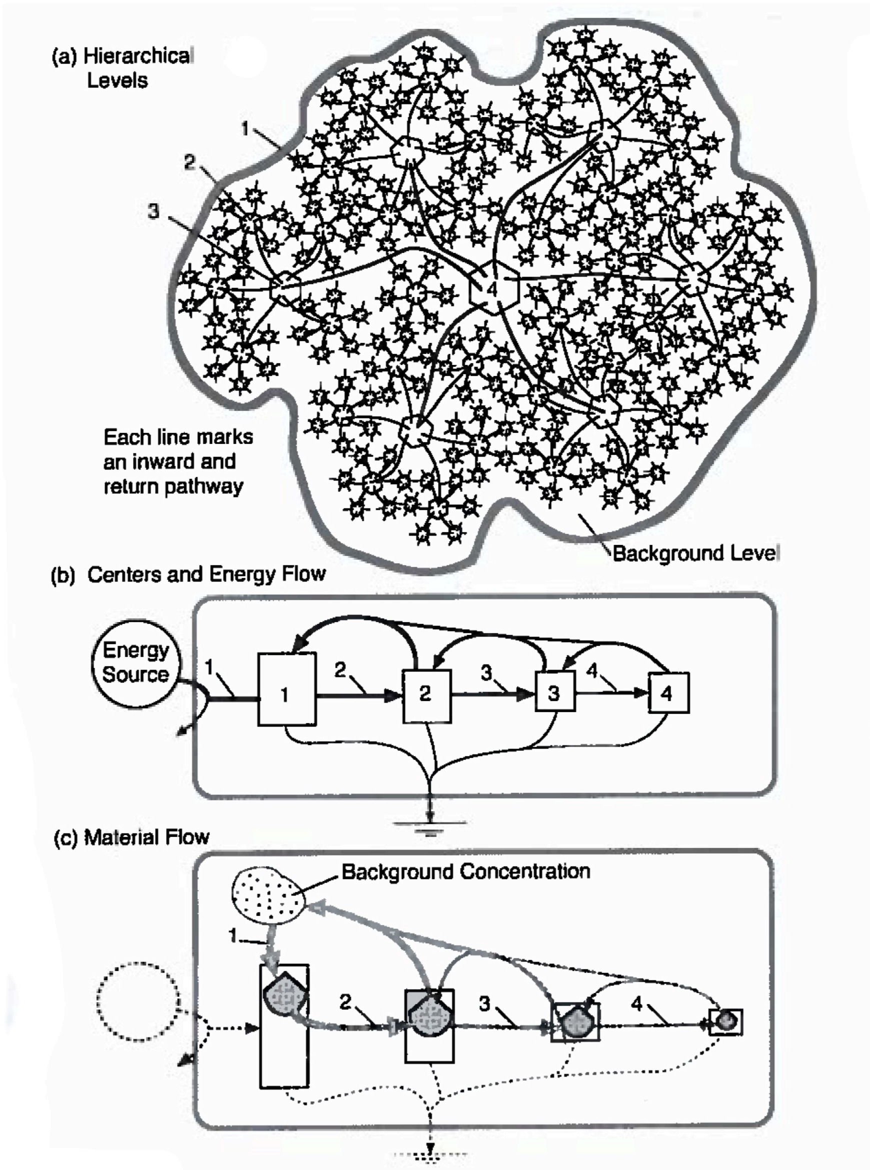

Figure 2.7. Spatial Patterns of Energy Hierarchy. (a) Spatial patterns of energy converging from smaller centers to larger centers; (b) energy systems diagram; (c) diagram of material concentration to the right and recycle to the left (Odum 2007, 77).

Energy hierarchy determines how ecosystems are spatially organized into centers. As trees are organized about their trunks, animals are organized around their nesting centers. Some animals cluster into groups to function more efficiently. Humans, ants, and cattle are some such species (Odum, 139). Figure 2.8 from Odum (2007) is an example of clustered human populations in a rural Kansas agricultural landscape.

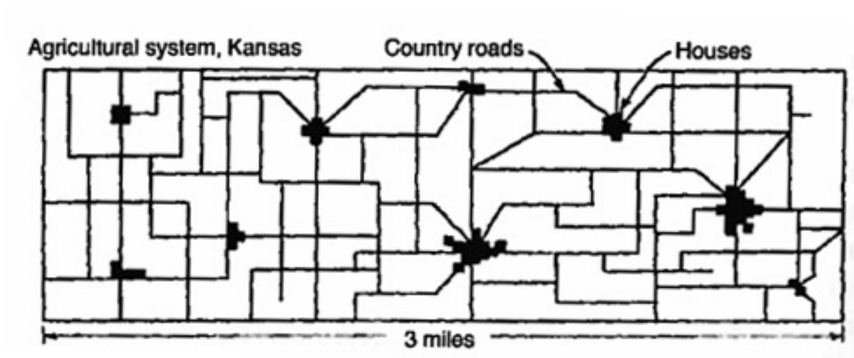

Figure 2.8. Clustered Populations Over an Agricultural Landscape (Odum 2007, 140).

Energy Hierarchy in Concentrating Materials

Spatial patterns occur across many scales (i.e. a single tree to a whole city and the surrounding land and towns that support it), but the scale of concern for this research is human scale and farm scale. Fossil energy has allowed that these two are not necessarily the same thing. Likewise, cities have grown to sizes unimaginable in pre-industrial societies. The reason is because of a relationship that exists between energy and material concentration. The second law of thermodynamics requires that to concentrate something, energy must be used otherwise the tendency of things is to disperse spontaneously. Figure 2.9 shows the role of energy in concentrating materials.

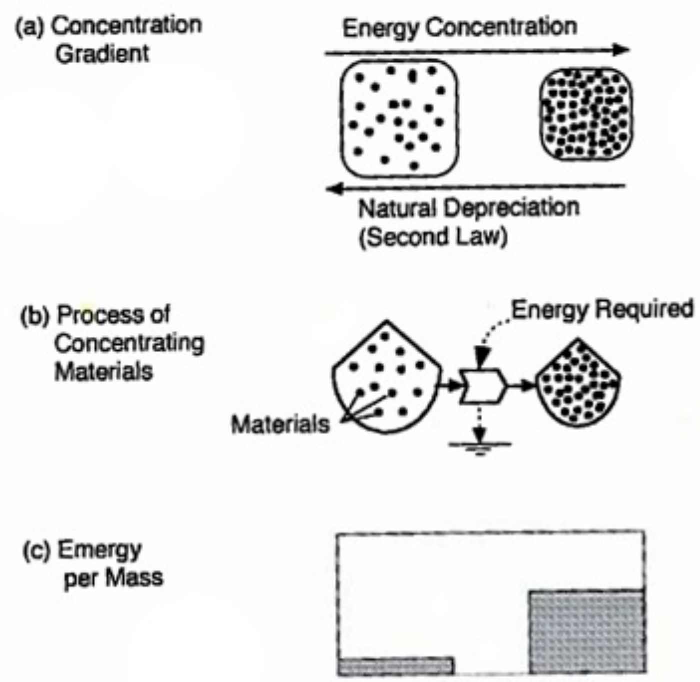

Figure 2.9. Using Energy to Concentrate. (a) The second law and concentration, (b) Energy process diagram; (c) Increase in emergy with concentrating materials (Odum 2007, 82).

Odum points out, "because available energy is used up in each transformation step, there is less and less available energy to do further concentrating" (Odum 2007, 83). Therefore, scale has to decrease with the quantity of concentrated energy, just as scale must decrease with the quantity of concentrated materials, and vice versa (Odum 2007). In other words, if there is not as much energy, fewer transformations can take place, and less can be concentrated.

Applying this to cities, Odum and Odum (2001) point out that cities will have to decrease and decentralize, spreading out more into rural areas with decreased energy availability (209). Regarding agricultural landscapes, cheap fossil fuels and fertilizers have also fostered large-scale farms with higher productivities and fewer workers. The farms are also spatially separated from the mostly concentrated (i.e. urbanized) populations they feed (Odum and Odum 2001). The reduction of available energy in the future has implications for the scale of agricultural landscapes, as well as new possibilities of what is utilized and considered "agricultural land." The scale of rural agricultural landscapes and the dispersal of people within them will be affected with less energy to concentrate materials. However, the amount of information in a landscape and energy inputs into the system may also be factors for determining the appropriate scale of farms.

Information in the Energy Hierarchy

Information is energetically expensive; it has the highest transformities of the energy hierarchy. Odum (2007) defines information as "the parts and relationships of something that take less resources to copy than to generate anew" (87). Information could include the text in a book, the DNA of an organism or a map. Emergy is required to generate information and emergy is also required to maintain and share it (Odum 2007). Energy flows and storages are carriers of information. For example, in agriculture the seeds of plants contain genes with biological information. The emergy it took to create the genetic information is a lot more than the actual energy in the seed. Information can also be cultural information, or passed down knowledge (Jackson 1984). In this case, the carriers are people and the information took a lot of upstream energy to develop. Passing on cultural information is much easier than trying to gain information from scratch. Passing on information is considered copying, and errors can be made in copying. Odum (2007) points out, "information is maintained by copies made faster than they are lost or become nonfunctional" (88).

Copies may develop variations due to local differences and errors. The copies that perform best are selected and copied again. Again, seeds are an example. Seeds are planted, and humans or nature selects those that are most successful in adapting to the local conditions to be disseminated and shared for the next growing season. This is very important in Andean agriculture—a low-energy input system. The Andean peasants rely on diverse biological information instead of pesticides to fight insects and diseases. In the margins of their small (less than one acre) fields, the Andeans grow potatoes and other crops along with wild and semi-domesticated species. They utilize these margins to create new crop varieties every year, taking advantage of the cross-pollination by birds and insects. In the case that weather, disease or insects wipe out the crop in the field, the farmers inspect the margins to see if any new species survived. If a successful species is found, the new, high-emergy information may be maintained and copied the next year. By taking advantage of the emergy of information, "agriculture is constantly renewing itself in direct response to what threatens it" (Berry 1977, 178).

The amount of information contained within a landscape varies depending on region and management practices. With lots of fossil energy, industrial agriculture has made it possible to produce food successfully without diverse biological information. In his essay, *A Search for the Unifying Concept for Sustainable Agriculture*, Wes Jackson (1984) makes a connection between energy use and information in agricultural landscapes and relates scale to both factors.

The Relationship Between Energy and Cultural and Biological Information

Wes Jackson addresses the issue of scale and energy input. However, his theory factors in cultural and biological information as well. By biological information, Jackson is referring to the information stored in almost every cell of an organism, which is responsible for its growth, development, maintenance, and reproduction (Jackson 1984). Cultural information is the information that can be handed down from one generation to the next. Much cultural information has been lost with the industrialization of farming that relies on fossil fuels. Comparatively, much more biological information exists than cultural, though humanity cannot afford to destroy biological information with the expectation that cultural information can replace it (Jackson 1984). Energy, on the other hand can be used to destroy biological capital, and its excessive use is the culprit for the loss of much cultural information regarding care for the land without fossil fuels. Fossil energy and the industrial economy have taken over many processes in agriculture that are biological in nature. Jackson points out that the loss of biological information must be substituted with cultural information or energy. In a society with cheap fossil fuels, usually more energy is substituted, resulting in degraded ecological capital (Jackson 1984).

According to Jackson (1984), scale can increase or decrease as the relationship between information and energy changes. Imagine scale as a fulcrum with biological and cultural information on one end and fossil energy on the other (see Figure 2.10). Scale can increase if biological and/or cultural information increases, without a change in energy input. An example provided by Jackson (1984) is a ranch in the Flint Hills of Kansas. The ranch is approximately 6,400 acres of native prairie supporting 1,700 head of cattle. One cowboy manages the land in his pickup truck, with additional help for fencing, branding, castrating, loading and unloading. The prairie is very diverse, rich with biological information, helping to prevent diseases and epidemics. The cultural information per acre is very low, and not many humans are required for the system to operate. The fossil energy input is minimal, and the scale is very large—the fulcrum is shifted to the left (Jackson 1984).

Another option is small scale. Jackson's example is of 6,400 acres in an Amish settlement in Indiana with an average of 80 acres per family, equaling around 80 families supported with a diversified agriculture on the acreage. Here, till agriculture is practiced, and biological diversity is decreased. Also, soil and water health have to be maintained now by humans where once the natural vegetation fulfilled this service. Jackson notes that the Amish substitute cultural information for biological information. For energy, human and animate power is employed, in addition to some small engine machinery. The human energy required is increased some 150-200 fold. Their production per acre is more than the Flint Hills ranch, and the produce is more diverse (Jackson 1984). For the Amish example, the fulcrum is situated somewhere in the middle.

The last example is a dryland farm in western Kansas operated by two farm families. They grow sorghum and wheat—their biological information is low and their fossil energy input is high. According to Jackson, erosion is not a serious problem and farming in this way can continue given available fuel (Jackson 1984). The fulcrum for the west Kansas farm shifts to the right, as scale is increased with energy input.

Odum's explanation of energy hierarchy demands that the scale of farms decrease without fossil energy input. This essentially aligns with Jackson's theory, as Jackson says scale must decrease without large energy inputs unless high biological and/or cultural capital exists.

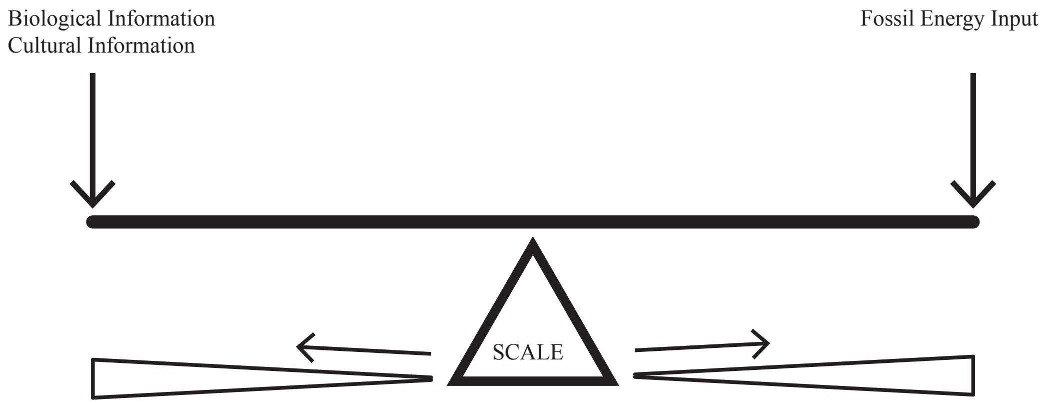

Figure 2.10. Interpretation of Jackson's Ideas on Scale, Information, and Energy. As cultural and/or biological information increases, scale can become bigger, shifting the fulcrum to the left. (Oppositely) Fossil energy input can increase scale, too (Graphic by author, 2014).

Energy Hierarchy as it Relates to Time and Storage

A temporal dimension exists in energy hierarchy, according to Odum (2007). All scales exhibit an accumulation-pulsing sequence, but moving to the right in the diagram in Figure 2.5, accumulations become longer and pulses appear to be more concentrated in time at these higher levels. Figure 2.5 also shows that less energy exists to the right. With the higher levels having less energy to feedback, "the higher levels can achieve concentration not only through spatial concentration but also by storing for a longer period and discharging in a shorter delivery time" (Odum 2007, 78). Odum says that pulsing is a result of the hierarchical self-organization of energy, and "the higher levels can do more with less by accumulating for longer times and delivering sharper pulsing" (78).

The sheep grazing on grass mentioned previously is an example of storage. The sheep eats the grass in an energy transformation and stores it. The storage supports feedback (i.e.

eating more grass). Odum notes that usually storage is associated with an energy transformation, and that feedbacks come from the storage. As Figure 2.5 shows, feedbacks go back up to the previous transformation unit, though sometimes feedbacks are longer and go up to other transformation units. Just as the sheep filled and discharged, storages fill and discharge in pulses. The storage size increases with each step along an energy transformation series. Odum says that this is a consequence of having longer periods of accumulation at higher levels. To be able to accumulate longer with less energy flow (i.e. to the right in an energy transformation series), a larger storage is needed. This is exhibited in nature as the size of animals usually increases along each step in the food chain as total energy flows diminish simultaneously (Odum 2007).

Territory, Turnover Time, and Transformity as a Measure of Scale

Odum recognizes territory and turnover time as helpful when understanding scale. In this context, territory is the size of the supporting land area of a storage (i.e. biological life form) and turnover time is the replacement time in which a storage fills and discharges; territory and turnover time vary according to level in a series of energy transformations. Odum notes, "a series of energy transformations really is a passage between scales of size and time in which transformity becomes a third measure of scale" (2007, 81). Figure 2.11 shows storage increasing with each transformation over time and increasing territory size. In other words, the storage size is related to the size of its territory of support and influence.

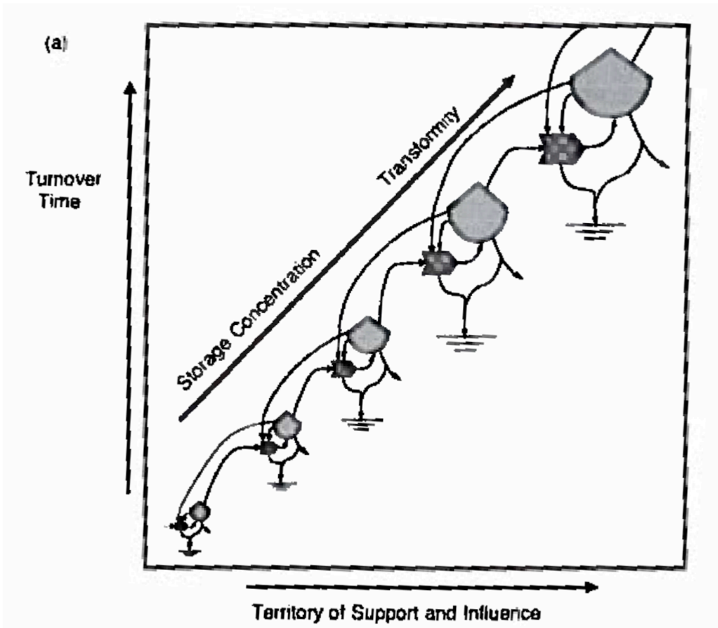

Figure 2.11. Energy Transformations on a Scale Diagram of Territory and Turnover. Storage and transformity increases with scale (Odum 2007, 80).

Changes between territory, turnover time, and transformity are evident in agricultural systems. At the soil level, the microorganisms have small territories and shorter turnover times compared to plants, which occupy larger territories and have longer durations. Feeding on plants are livestock with even larger territories and longer turnover times. Figure 2.12 below illustrates the territory and turnover time. The ability to store energy/emergy also correlates with increased territory and turnover time.

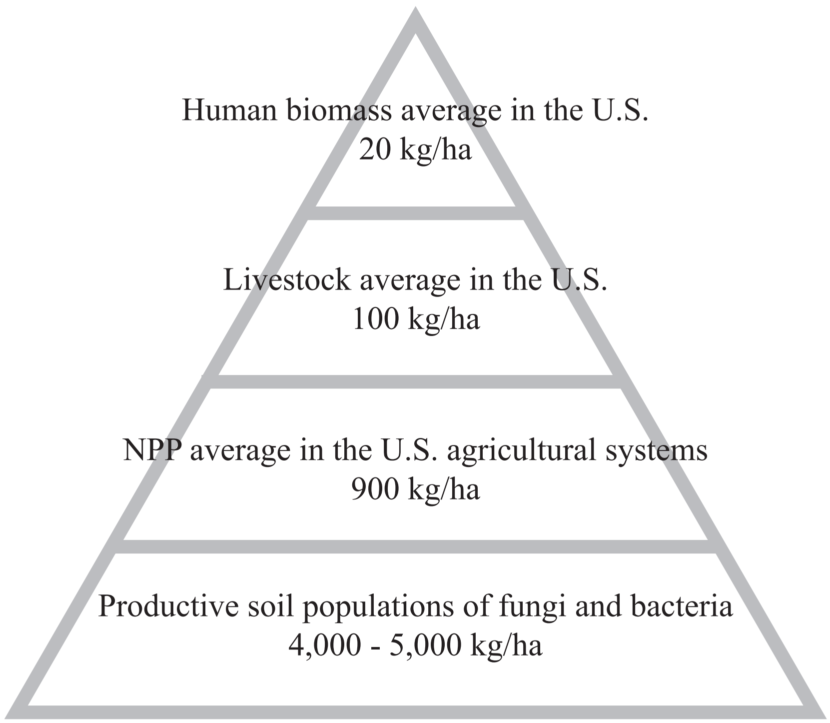

Figure 2.12. Biomass in kg/ha, Related by Territory, Turnover Time, and Transformity (the emergy/energy at a particular transformation in part of a series). This graphic shows more mass per area at the bottom and less at the top, a result of the loss of available energy with each transformation in the food chain. Note also the associated consequence of larger storage with diminished energy quantity (Numbers from Pimentel and Pimentel 2008, 20, 39-40; Graphic by author, 2014).

Energy Hierarchy Across Scales

An agricultural system contains many scales, from the cellular level to animals and people. According to Odum, each level in the energy hierarchy self-organizes the most power possible for its part of the system at the same time, following Lotka's maximum power law. For maximum power of the system, one part does not take precedence over another, but a "collective development" of all scales is necessary (Odum, 90). This point will be revisited in Chapter Five when discussing the interaction between the different scales.

Energy Hierarchy in the Landscape: Convergence

Energy hierarchy is evident in the landscape as streams flow down mountains to form rivers. As the water flows, power decreases as available energy is transformed and lost, but emergy increases, creating the highest empower concentration at the mouth of the river. Odum points out that these are often locations in the landscape from which civilizations begin, taking advantage of the convergence of natural energy. Depending on the particular landscape, streams may converge into lakes or flow underground and reappear as springs—both the lakes and springs being centers of emergy density (Odum 2007). Figure 2.13 depicts high empower concentrations within the landscape.

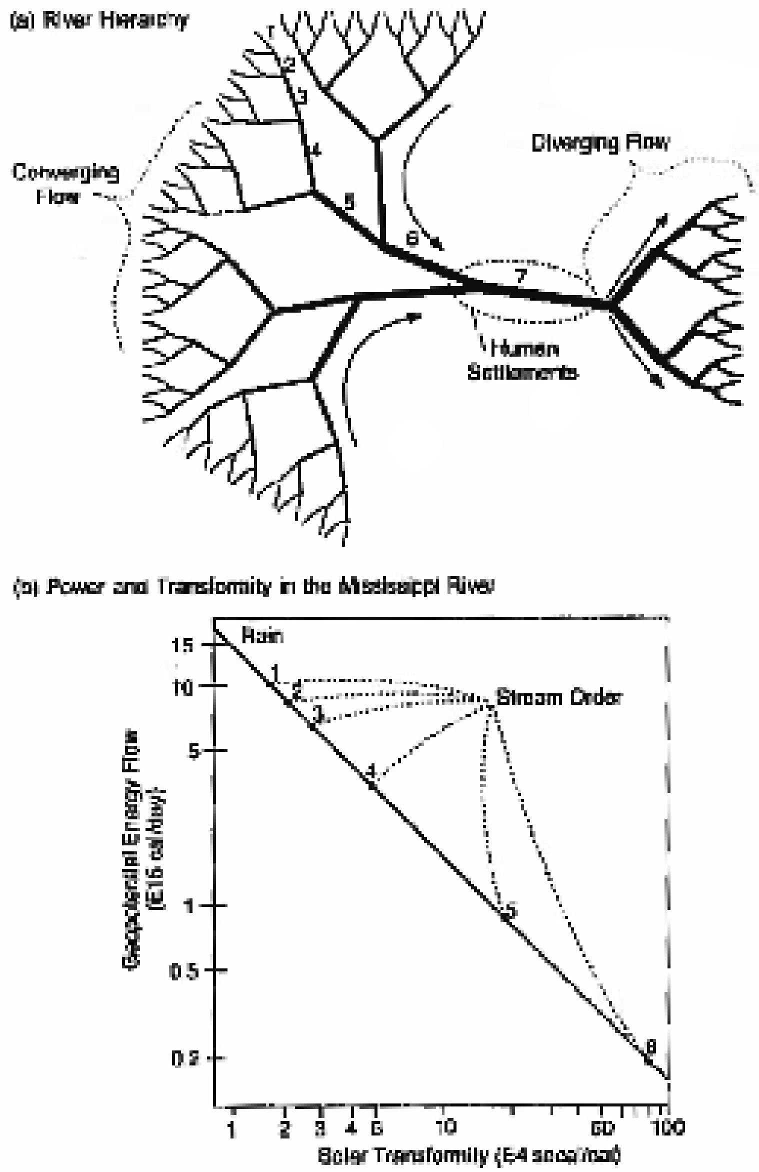

Figure 2.13. Energy Hierarchy in Streams and Rivers. (a) Civilizations often originate in natural areas of high empower density. (b) The relationship between geopotential energy flow and transformity in the Mississippi River watershed (Odum 2007, 119).

This concludes the discussion of energy principles. These principles will be the foundation for the design guidelines developed in Chapter Five. As evident in this review, the classic laws of thermodynamics describe single energy processes, and the law of energy hierarchy explains the behavior of energy as it is transformed along a series. In order to better understand how these energy principles, the next section explains biological and fossil energy flows around us and through us.

Biological and Fossil Energy

Light energy, known as solar radiation, comes from the sun and is absorbed by plants. Through the complex process of photosynthesis occurring in autotrophs (i.e. plants), specific wavelengths of solar radiation energize the reduction of CO_2 from the atmosphere, the release of oxygen, and the production of a vast variety of complex organic compounds in the form of biomass (Smil 2008). Heterotrophs (i.e. animals, fungi, and many bacteria) can then use these organic compounds directly (as herbivores or detritivores) or indirectly (as carnivores) to provide energy for growth and activity (Smil 2008). Smil (2008) recognizes photosynthesis as the most important energy conversion on earth as plants provide all of our food and our fuel. The latter is obtained through relatively rapid harvesting of wood or crop residues or extraction of transformed biomass in the form of fossil fuels (Smil 2008). Photosynthesis is essential for heterotrophic life.

These energy conversions facilitate the exchange of gases and nutrients between life forms. Autotrophs release the oxygen that heterotrophs need to breathe, and likewise, heterotrophs oxidize biomass and release CO_2 (Smil 2008), which plants later capture from the atmosphere. Additionally, the nutrients in the soil are taken up into the phytomass and transformed into organic compounds (Smil 2008). When digested by heterotrophs, these compounds provide nutrients (stores of energy) to the consumer. The energy efficiency of the consumer varies, and in animals a fraction of the ingested energy may be lost to fecal energy or combustible gas, or passes into digestible energy with losses to urinary or surface energy. Some of this energy may be metabolized with some heat losses, which vary according to activity level. This leaves a net metabolizable energy for maintenance, basal metabolism, and physical activity with minor losses (Food and Agriculture Organization "Food Energy – methods of analysis and conversion factors" 2002).

Energy also flows through nutrients. Nutrients, such as carbohydrates, lipids, and proteins cycle through heterotrophs, and upon being metabolized, yield energy (Smil 2008). With the energy losses to feces and urine, nutrients are lost to the consumer, but become available again to the ecosphere. Once back in the ecosphere, excrement along with dead plant and animal matter are a source of nutritional energy to detritivores and decomposers, which serve to make the nutrients available to autotrophs again, completing the complex cycle. Through each conversion, energy in the form of heat (i.e. low quality, long wave radiation) is lost to the atmosphere, satisfying the first law of thermodynamics, ensuring that energy is conserved. This type of energy is considered biological energy, in that it cycles through living things made of carbon.

Biological energy is different from fossil energy. All living things—people, animals, trees, fungi, etc., possess biological energy. Biological energy is transformed between trophic levels. For example, lots of solar energy shines down on a farm. Grass covers the pastures and captures solar energy, but only about 10% of the solar energy is transformed into chemical energy and the rest is dispersed as thermal energy because of the second law. A draft horse harvests energy from grass, and uses it, digesting the nutrients, and producing waste that feeds the soil. Again, energy quantity is decreased and quality increased with each transformation.

The soil then "digests" those nutrients into a form that feeds new plants that grow with the help of more incoming solar energy. In the process, humans may harness the horse's energy to perform work. Or humans may use a machine to do the work. A machine runs on a nonrenewable form of energy. The energy goes in as fuel, and comes out as mechanical work, thermal energy, and CO_2. Machine energy supports a highly simplified economy having two functions: production and consumption (Berry 1977). For humans to continue to extract work from the machine, more oil must be mined from the earth, and the cycle continues until the machine breaks down and is more expensive to repair than buying a new one. This stimulates the fiscal economy—more production and more consumption. At that point, the machine may become junk, or perhaps recycled, which still requires energy and more CO_2 emissions in order to turn the original materials into something else that it was not originally intended to be. The horse, however, once deceased is buried in the soil, and decomposes into nutrients and energy that feeds microorganisms, and eventually plants, passing on a renewable biological energy, continuing the Wheel of Life. Therefore, biological energy may be used wisely and perhaps to the advantage of ecological capital (i.e. building soil). This is something that has yet to be done with fossil-driven machine energy (Berry 1977).

However, humanity has developed an insatiable appetite for energy, especially in the convenient and seemingly "cheap" form of electricity. Biological energy does not supply the continuous power that fossil energy does. With the end of fossil fuels drawing nearer, humans have begun the search for renewable forms of energy. Berry (1977) questions the morality and effects of our energy use and what an infinite supply would mean for society. He asks,

> "Then what is desirable? One possibility is to tag along with the fantasists in government and industry who would have us believe that we can pursue our ideals of

affluence, comfort, mobility, and leisure indefinitely. This curious faith is predicated on the notion that we will soon develop unlimited new sources of energy: domestic oil fields, shale oil, gasified coal, nuclear power, solar energy, and so on. This is fantastical because the basic cause of the energy crisis is not scarcity; it is moral ignorance and weakness of character. We don't know *how* to use energy, or what to use it *for*. And we cannot constrain ourselves. Our time is characterized as much by the abuse and waste of human energy as it is by the abuse and waste of fossil fuel energy… If we had an unlimited supply of solar or wind power, we would use that destructively, too, for the same reasons." (13).

Despite the massive ecological damage made possible with fossil energy, the search is still on. The following section is a review of renewable options and the challenges of each. It is intended to provide awareness to the realities of renewables and the possibility that they may not save the world from an energy crisis. The second reason to discuss renewables is because at a small scale using locally renewable resources, local renewable energy may be a source that farmers can tap into when fossil energy becomes uneconomical. Even so, care should be taken. With regards to ecosystem services, Odum (2007) writes, "To tap these sources is to take power away from their roles in supporting civilization indirectly. Society depends on the environmental systems that run on planetary power" (107).

Renewable Energy Options and Feasibilities

The following renewable energy review approaches the feasibility of renewable energy options based on the physical limits that exist. This is also the approach taken by MacKay in his book, *Sustainable Energy—without the hot air* (2009). MacKay explores the possibilities and issues of renewable energy harvesting, and estimates the potential of renewable energy sources to understand how a world without fossil fuels would be powered. His approach is to see if we can sustain our current energy consumption by using renewables, not taking into account the economic feasibility, but the physical limits alone. MacKay crunches the numbers to understand the feasibility of renewable energy, and his work stands alone in the field, as it is one of the only comprehensive studies to have done so.

MacKay based his calculations mostly on his home country of Britain. These numbers would change for the US or any other location on the globe, but the physical constraints and challenges of each existing type of renewable energy is discussed: wind, solar, hydroelectric, offshore wind, wave, tidal, and geothermal. As stated previously, renewable energy sources do not have the high quality or high density of fossil fuels, and therefore the challenge with each type is the large land areas that must be allotted to capture renewable energy (Stremke and van den Dobbelsteen 2013, 4).

Wind Energy

One of the most promising sources of renewable energy is wind. Mounted on towers 100 feet or more above ground, wind turbines capture wind energy with wings shaped as airfoils. When the wind blows, low pressure forms on the downside of the blade and the high pressure on the up side pushes the blade down, creating rotation. Wind energy generation is dependent on the power per unit area; the power per unit area is a function of the wind speed of a particular location, and wind speed fluctuates irregularly. The demand for energy also fluctuates, but the electricity grid cannot store the energy harvested during peak wind hours for use during peak demand hours as the existing fossil fuel system operates by ramping up their supply to meet demand times, and then decreasing generation when demand decreases.

For wind energy, these challenges may be overcome in the future by pumped storage, which uses the cheap energy produced during times of low demand and high wind to pump water up to a higher level, then regenerate that electricity when it is needed (MacKay 2009). Another option that could help further the stability of wind energy is electric car battery chargers that store energy collected when the wind blows, but switch off when the wind drops or demand increases (MacKay 2009). Of course, in a non-fossil world the wind energy would have supply sufficient energy to manufacture and transport the batteries too. Still, MacKay sees this as the perfect match for wind energy and electric vehicles, as he offers several ideas to overcome the lulls in windy periods and slews of increase or decrease in demand. However, large amounts of materials such as steel and concrete would be needed for pumped storage stations, and elements like nickel and cadmium would be required for a huge fleet of storage batteries. Not only do natural resource and environmental challenges exist, but economic and political issues do too.

On August 14, 2013, Dianne Cardwell of the New York Times reported issues associated with wind energy production, pointing to the location of wind turbines being in sparsely populated areas that do not have transmission lines big enough to carry all the power to more densely populated areas, and the grid managers, who are challenged with meeting the demand instantaneously, opting for the reliable fossil fuel sources and calling for curtailments, or cutbacks, in wind power. From a business standpoint, wind farm developers and operators are losing money when wind energy production is curtailed. In the article, David Hallquist of Vermont Electric Cooperative said that the curtailments cost the Vermont wind farm more than 1.5 million dollars in the winter of 2012-2013. The difficulty lies in managing the fluctuating power flow from wind with a system that is designed for a steady power flow, which fossil fuel plants are able to produce.

Amory Lovins and others at the Rocky Mountain Institute optimistically say that these obstacles can be overcome, and that constructing wind turbines on suitable windy sites on available land in the U.S. could generate 9.5 times as much electricity as the U.S. used in 2010 (Lovins 2011). Based on a 2010 study by the National Renewable Energy Laboratory and AWS True Wind, the wind potential is estimated at 13,000 GW per year. However, the land required to harvest that much energy includes all the land with a suitable wind resource except "areas unlikely to be developed," such as wilderness areas, parks, urban areas, and water features (United States Department of Energy, "New Wind Resource Maps and Wind Potential Estimates for the United States" 2014). Besides the fact that this many wind turbines would take up a lot of agricultural land, the resources and energy to build such a wind fleet is questionable. Also, Lovins is only accounting for electricity; the U.S. also consumed 19,192 thousand barrels per day of petroleum in 2010 (U.S. Energy Information Administration 2014), which equates to approximately an additional 1,370 GW per year of liquid fuels.

Solar Energy

Solar energy is another renewable energy alternative. Solar energy can be captured in four ways: by solar thermal collection or direct solar heating, solar photovoltaic (which generates electricity), solar biomass (using biomass to make biofuels, chemicals, or building materials), and as food for humans and animals to eat (also solar biomass). The amount of solar energy that can be harvested depends the available power density for a particular area—determined by distance from the equator, the time of day, the season of the year, and the cloud cover. For example, the average power density in Atlanta, Georgia is 182 W/m^2, and the global mean is 173 W/m^2 (MacKay 2009).

The solar thermal process collects heat energy (i.e. low quality heat, not electricity) from panels on rooftops and heats water. A main issue with solar thermal is that heat energy is low quality and cannot be shared through the electricity grid, hence, where the heat energy is harvested is where it should be used. This type of energy generation is problematic in cities where there is a large volume of people, but little rooftop area per person, though it may be beneficial for warming water in agricultural landscapes. Also, as with other forms of solar, this energy is irregular throughout the year (MacKay 2009).

The second way solar energy can be transferred into power is through solar photovoltaic (PV) panels. Most panels are 10% efficient, with the more expensive ones performing with 20% efficiency at turning solar energy into electrical energy. Photovoltaics with 20% efficiency are nearing the theoretical limit, and efficiency is not expected to improve by much in the future (MacKay 2009). PV panels, like solar thermal panels, capture the most energy on south-facing roofs in the northern hemisphere, and these two forms of solar energy collectors would be competing for space on rooftops if used together.

Another option is solar farming, which spreads PV panels out over land to capture energy. Considering the negative consequences that come from impervious pavement and reducing phytomass land cover, solar farming may be ecologically destructive in some regions. This type of power generation may also compete with agriculture and recreation land uses. Regardless of the ecological implications and physical limitations, MacKay estimates that a solar facility the size of Arizona could provide enough energy for 500 million people in North America (MacKay 2009).

The third and fourth ways to transform solar energy to useful energy are through growing biomass from which to extract it. The biomass may be burned in power plants to produce the electricity or substituted for oil. For oil substitution, high-energy crops, such as sugarcane and corn, may be grown and converted into ethanol and biodiesel. Also, fermenting by-products such as rotting vegetables or animal feces release methane that may be trapped and burned. Lastly and most basically, the biomass may also be eaten to provide energy to sustain humans and animals (MacKay 2009). Crops grown for oil-substitution and food may often compete for agricultural land (Lovins 2011). Other large competitors for corn are livestock farmers that feed the grain to cows, pigs, and chickens. This will be discussed in more detail in the following section discussing modern agriculture.

Growing plants for food is the most efficient and direct way to supply food and energy to humans because it cuts out any additional transformations and, therefore, further efficiency losses. Biomass grown for biofuels is cleaner to burn than oil or coal, emitting fewer greenhouse gas (GHG) emissions (Sullivan et al. 2010). But, before considering growing crops for fuel, recall that we are already degrading our ecological capital and therefore decreasing our ability to provide food in the future because of our current destructive farming methods. Regardless, Lovins is again optimistic. He acknowledges the interference biofuels may have with food production but says that by using crop residues and inedible prairie grass we can avoid that problem. He continues by saying that researchers and companies are progressing and “these advances promise big gains in the fight against climate change” (Lovins 2011, 66). However, crop residues are critical in agricultural systems that aim to reduce energy dependence. To take crop residues (i.e. organic matter) off the land is to degrade soil structure, decrease aeration, decrease the water holding capacity of the soil, take away the ability to buffer against pH changes in the soil, decrease the cation and anion exchange capacities, remove a huge reservoir of slow-release nutrients and take away the energy source for soil fauna and microorganisms that are responsible for the improved physical and chemical attributes of the soil (Allison 1973; Pimentel and Pimentel 2007). Without organic matter, the productivity of an agricultural system declines without external inputs to substitute for the services provided by organic matter. Lovins' other idea of using inedible prairie grass contains a fallacy too. It is true that humans cannot consume prairie grass directly, but we can consume it indirectly as meat. Animals can harvest the grass and recycle nutrients in the process, maintaining the productivity of the prairies. Again, removing prairie grass requires removing nutrients. Also, this approach is only offering a reduction in CO_2 emissions. Even so, the amount that biofuels are estimated to contribute are minimal compared to other renewables (Lovins 2011).

Hydroelectric Power

Hydroelectric power is derived from the potential energy of contained rainfall, usually by damming rivers. The gravitational power of water (power per unit area of land on which the rain falls and is collected) is a function of the rainfall amount, the density of water, gravity, and the average altitude over which the water will fall (MacKay 2009). For the U.S., hydroelectric power is considered feasible for the Northwest, as the potential varies by altitudes and climates. A study published by the National Renewable Energy Laboratory estimates hydropower to have a potential of 60 GW in the U.S. (Lopez et al. 2012). This amounts to 4.5 kWh per person per day distributed evenly across the current U.S. population. Smil (2008) notes that North America has already exploited 70% of the technically feasible capacity. Also, there are negative effects of damming rivers: harmful ecosystem alteration, the large amount of land required, adverse effects for fish populations, low dissolved oxygen, impacted water flows downstream, water table effects, and social impacts (Schramski, "Fossil-Fueled Civilization: Patterns and Trends"). As Odum (2007) points out, previous to being dammed, the emergy of the rivers were "already being used in support of the landscape's economy" (120). The water table and downstream water flows are important issues for farmers. The positive aspects of damming rivers include control of energy reliability, creating protected drinking water, irrigation, fishing and recreational uses, and flood control (Smil 2008).

Before hydroelectric dams, a more primitive method was used. A waterwheel was used to harvest energy from water as early as the first century BC (Smil 2008). By the 1900s, thousands of waterwheels were operating, producing continuous power averaging 50 kW, making it the most efficient preindustrial energy converter (Smil 2008). The largest known waterwheel ever built was constructed on the Isle of Man in 1865; it delivered approximately 200 kW of power (Smil 2008). Waterwheels powered many previously manual tasks such as sawing, milling, and oil pressing (Smil 2008). Though waterwheels are a proven long-term successful generator of power, they are limited by the amount of power and lack of mobility. Still, at a small scale, waterwheels may be feasible in a non-fossil energy world.

Offshore Wind Energy

Offshore wind is an appealing option for renewable energy as winds over the ocean are stronger and steadier than those on land. Offshore wind energy is captured like wind energy on land, except offshore turbines are mounted on towers with foundations in the sea floor. Shallow offshore depths are much more feasible to build on, both physically and economically, though the structures are nearly twice the cost of wind turbines on land. Deep offshore wind harvesting is currently not economically feasible (MacKay 2009). Other issues include the destructive effects of seawater on the turbines. After 18 months of operation, turbines at the Horns Reef wind farm in Denmark had to be dismantled and repaired (MacKay 2009). Such large amounts of materials are required to construct the turbines in the first place that the feasibility of building and repairing so many turbines is questionable in terms of finite material constraints. Also, hurricanes and big windstorms can cause damage to wind turbines, which require repairs.

According to a 2010 report by the National Renewable Energy Laboratory, U.S. offshore wind theoretically could provide 4,150 GW of electricity when running at maximum turbine capacity (Schwartz et al. 2014). The ocean area required to provide that amount of energy is all the area within 50 nautical miles from the shore with minimum wind speeds of 7 m/s (~16 mph), without excluding areas that may be needed for shipping or fishing, or those with other technical considerations (National Renewable Energy Laboratory, "NREL Releases Estimate of National Offshore Wind Energy Potential" 2014). Following MacKay (2009), assume one-third of this area is developed with offshore wind equipment. Operating at maximum capacity full-time, offshore wind could contribute 105 kWh per person per day in the U.S. Assuming a linear relationship between the figures MacKay used for kWh/day and tons of steel and concrete needed for the construction of the offshore turbines, 131 million tons of concrete and steel is needed to construct enough turbines. The area required assuming 5 MW of wind turbines in every square kilometer meeting the NREL report characteristics would be 830,000 sq km (706,567 sq mi). Reducing this area to one-third requires 610,000 sq km (235,520 sq mi), or an area nearly four times the size of Georgia. Though offshore wind seems to have a lot of potential, many obstacles still exist. The amount of resources (i.e. concrete and steel) needed to construct enough offshore turbines to generate two-fifths of the average U.S. citizens daily consumption would require an “industrialization of the environment so large it is hard to imagine” (MacKay 2009, 62).

Wave Energy

As the wind rolls across the oceans, waves are produced. Waves deliver power per unit length of coastline (MacKay 2009). Defne et al. (2009) found that the wave power potential of the southeastern U.S. coastline is approximately 9 kW/m at 50m offshore for North Carolina, South Carolina, Georgia, and Florida. The power increases to approximately 15 kW/m farther offshore (Defne et al. 2009). If all of this power was harvested with 100% efficiency along every meter of coastline for these four states, the power generated would be 10 kWh/d/p and 17 kWh/d/p, respectively, for the population of these four states using the 2010 U.S. census numbers. Making bold assumptions, assuming the wave-machines convert wave power to electricity with 50% efficiency and they span approximately half of the southeast U.S. Atlantic coastline, the estimates fall to 2.5 and 4.3 kWh/d/p for the 42.6 million people in these states. The average American currently consumes 250 kWh/d. These values hardly add up for all the inputs that would be required.

Tidal Energy

Tidal energy, also called lunar energy, is produced by the rotational energy of the earth and the gravity between the earth and the moon, which is slightly imbalanced. The tides are a result of the ocean gravitating towards and away from the moon in order to account for the slight imbalance between the moon’s gravitational forces and the centripetal force that is required to keep the earth and moon rotating around the common center of gravity. The tides vary in size by the phase of the moon, and there are two high tides and two low tides a day (MacKay 2009).

To harvest energy from these tides, essentially an electrical generator with a turbine is underwater, spinning and capturing the potential energy of the water rushing in and out of a tide pool—perhaps an estuary or a bay. The maximum tidal amplitude on the Atlantic Coast occurs near the middle of the Georgia Coast around Sapelo Island, where it reaches 2-3 m. Assuming a 3 m range, the maximum power that could be generated is 2 W/m^2. To generate any sizable amount of power with this power density would require huge, several hundred square km size areas. The Rocky Mountain Institute does not foresee ocean wave or tidal energy to be a likely resource anywhere along the Atlantic or Gulf Coasts (Lovins 2011). In addition to the lack of efficiency, marine life harm is a concern with underwater turbines.

Geothermal Energy

The two sources of geothermal energy are the radioactive decay in the crust of the earth and the heat rising out through the mantle from the earth's core. The heat in the core is "being topped" by tidal friction from the gravitational forces acting on the earth. Geothermal energy provides a constant supply, unlike wind and other fluctuating renewables. Heat may be extracted from hot spots or ordinary locations, with the hot spots being the areas most likely to be developed first (MacKay 2009).

In 2006, MIT published a study on the potential of geothermal in North America. The study states, "With a reasonable invest in R&D, EGS (enhanced geothermal systems) could provide 100 GW_e or more of cost-competitive generating capacity in the next 50 years. Further, EGS provides a secure source of power for the long term that would help protect America against economic instabilities resulting from fuel price fluctuations or supply disruptions" (MIT 2006, 1-3). MacKay (2009) points out that 100 GW of electricity is only 8kWh/d per person divided between 300 million people. But, the extraction of heat energy from the earth may have unforeseeable negative impacts similar to the effects we are now witnessing from the combustion of fossil fuels and the heat-trapping gases that are being released into the atmosphere. Already, research has shown that geothermal energy extraction carries environmental and social consequences realizable in the short-term. At a shallow depth (< 400 m), extracting heat from the earth can create a cold plume (Hahnlein et al. 2013). The lack of heat in this localized area results in a temperature deviation of the subsurface and groundwater, impacting ecosystem services, flora, fauna, and drinking water reservoirs (Hahnlein et al. 2013). Hence, geothermal systems are limited by the rate at which earth can supply heat from its hot interior (MacKay 2009), and must be managed to maintain the balance between the net energy discharge and recharge in order to be productive on a time scale of 100 to 300 years (Axelsson 2010). This review of geothermal reinforces the limits of renewable energy. Though more research and technology may aid in the transition off of fossil fuels and help protect against economic instabilities, it does not seem likely that renewable energy of any kind will ever be able to meet our current demand.

Renewable Review

As the writer Isaac Asimov said in 1988, "The law of conservation of energy tells us we can't get something for nothing, but we refuse to believe it" (Thompson and Sorvig 2008, 262). Yet, we are still pouring many resources, including fossil energy, into trying to make renewables sufficiently replace fossil energy. Smil (2008) points out that trying to fuel modern societies with renewables will require diffuse energy flows to be concentrated “to bridge power density gaps of 2-3 OM” (383) as shown in Figure 2.14.

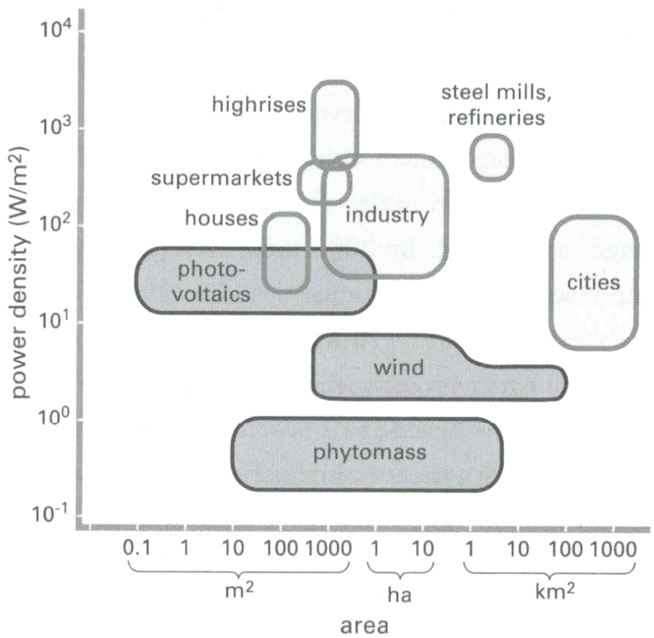

Figure 2.14. Typical Power Densities of Renewables and Energy in Modern Society (Smil 2008, 383).

The fossil energy that supports the structure of modern society simply will not exist. Changes must come about, as Odum and Odum pointed out (2001). These changes may include sacrificing luxuries, driving or flying less and walking more, or a decreased food supply. However, food is a most basic need that will still exist in a low-energy society. Smil (2008) states, “Agricultural adjustments in fully solar societies would be equally profound. Intensive field cropping is a space reduction technique made possible by rising energy subsidies in order to support increasing population densities” (384). If all these experts are correct and we must soon find a way to survive without excessive cheap energy, then how do we gauge the dependency of agriculture on subsidized fossil energy in order to understand our vulnerability? To help understand this, researchers do energy analyses.

Energy Analyses

To understand energy flows and the amount of fossil energy required for various goods and services delivered to humans, often energy analyses are employed. Energy return on investment (EROI) is a ratio of energy output to the energy input that is calculated with the intention of accounting for all the energy that went into production (i.e. indirect or embodied energy) of a particular good such as a steak or a wind turbine and comparing it with the energy output of that good. Once analyzed we can understand how much fossil energy (i.e. subsidized energy) was required to make that specific good (Kubiszewski, Cleveland, and Endres 2013; Schramski et al. 2013). The embodied energy takes into account the energy used in mining, manufacturing, transport, construction, operation, decommissioning, and other stages in the lifecycle of the processes that create a specific good (Kubiszewski, Cleveland, and Endres 2013).

EROI analyses are difficult, as mentioned below, and the science behind them is still developing. Because EROI analyses attempt to simplify the complexities of energy flows into a single number (e.g. a ratio of output to input), without considering other contextual information, many important aspects are left out (Giampietro, Mayumi, and Sorman 2010). As Smil (2008) points out, EROI completely disregards the quality of delivered energy. However, current state-of-the-art input-output analyses produce sufficient results to gain an idea of magnitudes and trends (Schramski et al. 2013). The next chapter will review energy analyses for agricultural systems.

EROI analyses exist for renewable energy generators. Of the renewables above, wind has the best return; solar thermal and nuclear energy have the lowest returns, as shown in Figure

2.15. Wind energy with an EROI of approximately 18 seems promising. However, how can the full amount of energy invested in a product or good be measured? Wes Jackson, founder of the Land Institute, and his colleague, Marty Bender, performed a ten-year study of 210 acres at the Land Institute in Salina, Kansas. The purpose was to understand the amount of food that could be produced using only solar power to "pay all of the energy bills for the operation using conventional crops" (Jackson 2010,11). Bender attempted to calculate the embodied energy in everything that was used on the farm, down to a replacement bolt. Energy was required to go to the store to get it in a pickup truck, to mine the ore the bolt was made of, to build the machines that mined the ore and manufactured the ore, and to build the buildings the manufacturing took place in. Also, what about the energy required to keep the workers in the mining and manufacturing functioning? When asked where other researchers Bender was citing stopped in their energy assessments, Bender replied, "When they get tired" (Jackson 2010, 11). The point, as stated by Jackson, is "what we failed to appreciate is how quickly the 'scaffolding' of civilization became so elaborate and so energy intensive and so unknowable" (Jackson 2010, 11-12). The director of the Stanford Knowledge Integration Laboratory, Jack Alpert, echoes this point. Alpert is concerned that without fossil energy, the EROIs of renewable energy sources will be too low to support a renewable energy society (Video: How Much Degrowth is Enough? 2012). This is an important aspect of consideration for manufactured renewable energy generators. Energy Analyses have been completed for renewable energy sources as well as agricultural operations. The next chapter contains EROI analyses of modern agricultural operations. The next section is on the atmospheric changes that are occurring as a result of fossil fuel combustion.

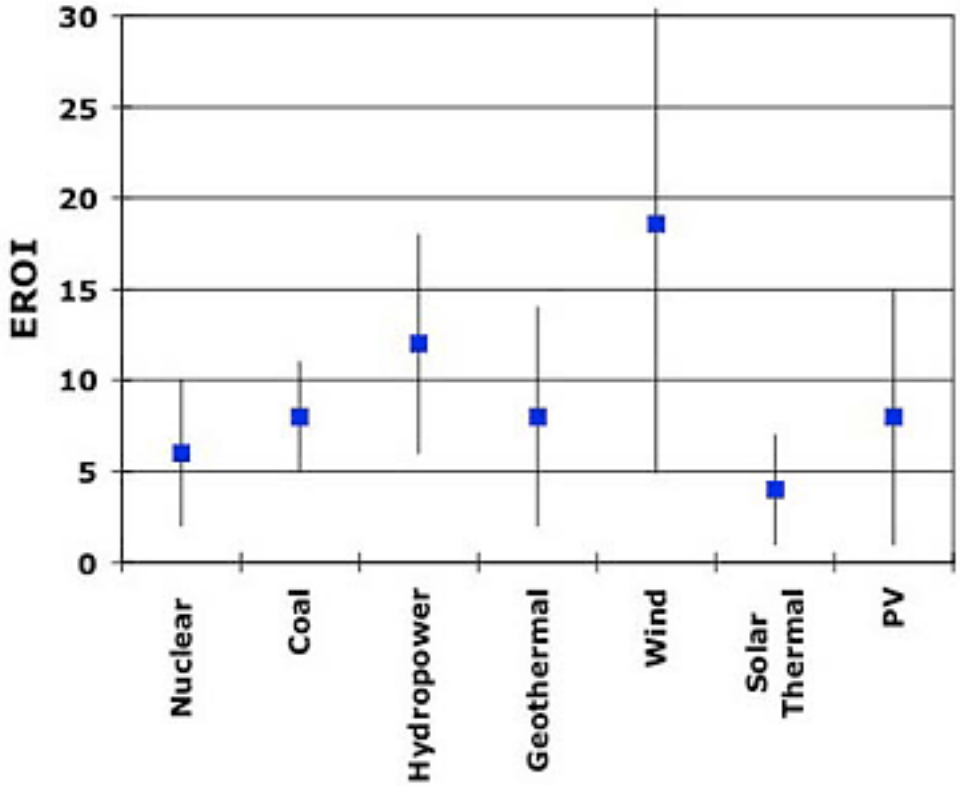

Figure 2.15. EROI of Renewable Power Generators (Kubiszewski, Cleveland, and Endres 2013).

Atmospheric Changes from Fossil Energy Use

Much work has been achieved with the utilization of fossil fuels. The second energy law ensures losses during a transformation, and heat energy is a byproduct of the combustion of fossil fuels. As fossil fuels are ancient stores of biomass (i.e. carbon), burning them releases carbon as a gaseous byproduct. The carbon byproducts are invisible, and they are negligible unless they exist in large quantities. After 200 plus years of burning fossil fuels, these gases now exist in large quantities in our atmosphere. The percentage of these combustion byproducts in comparison to the other gases in our atmosphere may not seem that large, but when considering the equilibrium and balance of earth, it is apparent that the amount of gases being combusted and released into our atmosphere is enough to offset the atmospheric equilibrium.

The main gas released when fossil fuels are burned is carbon dioxide. CO_2 flows into the atmosphere from the biosphere and oceans at approximately 770 Gt per year, but this amount also flows out. This flow is considered *natural*, and it cancels out (MacKay 2009). The combustion of massive amounts of fossil fuels releasing CO_2 adds a new flow to the atmosphere, and this new flow is the concern. Plants help by taking in the CO_2 during photosynthesis, but deforestation and desertification are occurring worldwide, increasing the problem of too much CO_2 in the atmosphere. Figure 2.1 shows the change in biomass in terms of potential energy from 1900 to 2000. The biomass was reduced from 23 ZJ in 1900 to 18 ZJ in 2000 (J.R. Schramski, submitted for publication, personal communication). Simply put, the plants that once existed to absorb the CO_2 are gone.

The issue with extra CO_2 in the atmosphere stems from the physical properties of the molecule. CO_2 absorbs solar radiation of different wavelengths. H_2O is also present in the atmosphere and it, too, can absorb various wavelengths of light; in fact, water vapor is the most effective greenhouse gas on the earth, allowing the earth's surface to average 15°C and support life as we know it. Visible light can pass through the atmosphere with negligible impedance, but much of the infrared flux (i.e. heat) with longer wavelengths is absorbed by water and CO_2 and, to a lesser degree, O_3, CH_4 and N_2O (Smil 2008). This absorption of incoming radiation affects the quantity and quality of the solar radiation reaching earth's surface. Once the shortwave visible light that made it through the atmosphere is transformed on the earth's surface, it is sent back out as longwave (i.e. infrared, heat) maintaining the planet's energy balance. As it leaves, some of it is trapped in the CO_2, O_3, N_2O and CH_4 molecules. The absorbed heat is then reemitted in all directions, creating the greenhouse effect (Smil 2008). The increased concentrations of these gases results in more trapped heat that is unable to leave the atmosphere

(MacKay 2009). This extra heat, forcing our planet out of equilibrium, is the basis for climate change.

Additionally, cleared and developed land has shifted the balance in terms of albedo[4] as well. The single largest anthropogenic cause of an approximately 0.01 albedo increase during the past few hundred years is deforestation (Smil 2008). Reflection of shortwave radiation begins in the clouds, but a large majority of the reflection occurs on the earth's surface. The shortwave radiation that is not reflected is absorbed and transformed into longwave radiation. Snow reflects radiation well compared to asphalt, which absorbs it—hence, the heat island effect. Snow and ice melt decrease the amount of shortwave energy being reflected into the atmosphere and have an effect on the earth's radiation balance. Global temperatures and the amount of heat being absorbed by the ocean are both affected by changes in albedo (Smil 2008).

How much more CO_2 is in the atmosphere than would naturally exist? Scientists estimate that the 1850 pre-industrial level of CO_2 was 280 parts per million (ppm), and by 1958 the CO_2 level at Mauna Loa, Hawaii averaged 320 ppm, rising to 370 ppm by the turn of the century (Smil 2008). In June 2013, the CO_2 level average was 398.6 ppm, and June of 2014 averaged 401.14 ppm ("Trends in Atmospheric Carbon Dioxide"). Equally as important as CO_2 in the atmosphere are the other anthropogenic gases that absorb outgoing infrared radiation. They are called greenhouse gases, because they also trap outgoing heat energy and contribute to the greenhouse effect. These other gases are in lower concentrations than CO_2, but because of their specific absorption rates, they intercept more outgoing infrared radiation than CO_2. The natural gas and coal mining industries are significant sources of methane (CH_4), but methane is also a natural byproduct of anaerobic fermentation in rice fields and enteric fermentation in ruminates

[4] Albedo is a measure of the high-quality shortwave radiation that is reflected from the earth's surface and scattered back into the atmosphere without changing wavelengths (Smil 2008).

(Smil 2008) such as cows and sheep. Methane rises from landfills, too (Smil 2008), as biological wastes ferments among the Styrofoam and plastics and other manmade wastes. The third most important greenhouse gas, nitrous oxide (N_2O), comes from denitrification and fossil fuel combustion (Smil 2008). One source of denitrification is the use of nitrogen fertilizers for agriculture (Mulvaney et al. 1996). During the process of denitrification, nitrate (NO_3^-), an available form of nitrogen for plants, reduces to nitrous oxide, and then to nitrogen gas (N_2). The nitrogen is lost to the farmer (physically and economically) and nitrous oxide is released into the air, trapping more heat in the atmosphere.

These greenhouse gases, CO_2, CH_4, and N_2O, have different physical properties that allow each one to trap a specific wavelength of outgoing infrared. To express the potential of each gas to trap heat, it is customary to measure it relative to carbon dioxide, or in equivalent amounts of carbon dioxide (CO_2e), where "equivalent" means having the same heat trapping effect over 100 years (MacKay 2009). In 2000, 34 billion (metric) tons of CO_2-equivalent was released (MacKay 2009). Divided by the world population of approximately 6 billion in 2000, this totals an estimated 5.5 tons of CO_2-equivalent per person. However, distribution was not equal worldwide. Americans released over 24 tons of CO_2-equivalent per person in 2000 (MacKay 2009), leaving those in less-developed countries with a much smaller portion of the effect.

The physical qualities of CO_2 are understood, and the quantities that are in the atmosphere are known. It is the implications of the physical effects that this unbalanced flow will have on the earth that is debated. Scientists predict a range of things, but most likely tropospheric temperatures would rise by 2°C-4.5°C, creating irregular higher seasonal temperatures, an accelerated water cycle, a change in precipitation patterns, and a rise in ocean levels. This would create an imbalance in the oceans as the surface of the water would absorb more CO_2 and the pH would decline, possibly as much as 0.4 units by 2100 (Smil 2008). The environmental, health, and socio-economic consequences are unknown.

The fossil fuels that supply the world with energy are largely responsible for the elevated CO_2 levels in earth's atmosphere (Smil 2008). Of all the energy supply, each year 1.5% of the total primary energy supply (TPES) goes into the production of nitrogen fertilizer for increased crop production, one of the major factors that has allowed for the sharp increase in human population (Smil 2008). This increased crop production comes with a price, at least in an ecological sense, and the current production model will not last—the energy currently used to subsidize it is running out.

Chapter Two Analysis

This first part of this chapter reviews the principles of energy and explains how energy flows through the landscape. All offer insights on designing for energy efficiency. These laws and principles are complex and much is still unknown. This, however, is a start to understanding agricultural landscapes from an energy perspective in order to adapt in the future. Table 2.2 is a list of the energy principles that will be used to develop the energy-based design guidelines that will address reducing energy use in agricultural landscapes.

Table 2.2. Energy Principles.

Energy Principles – Basis of Design Guidelines
First Energy Law
Second Energy Law
Spatial Patterns of Energy Hierarchy
Energy Hierarchy of Concentrating Materials
Energy Hierarchy of Information
Energy Hierarchy in Time and Storage
Influence of Territory, Turnover Time and Transformity on Scale
Energy Hierarchy Across Scales
Converging Energy

The last half of the chapter is a review of the feasibility and possibilities of renewable energy sources. The low power densities and storage issues present challenges yet most experts agree that energy use must be reduced in the future (Odum 2007; Pimentel and Pimentel 2008; Smil 2008). The science of energy analysis is reviewed towards the end of the chapter, followed by a discussion of the pressing consequences of a changing climate.

CHAPTER 3

MODERN AGRICULTURE

"The high yields from industrial agriculture generated a very cruel illusion because the citizens, the teachers, and the leaders did not understand the energetics involved and the various means by which the energies entering a complex system are fed back as subsidies indirectly into all parts of the network." -H.T. Odum, Environment, Power, and Society for the Twenty-First Century, 2007 (190)

In the United States, modern agriculture is energy intensive. This fact has many social and environmental consequences. The first part of this chapter includes a brief overview of many of these issues. The last half of the chapter details energy analyses that have been conducted on agricultural operations. These analyses provide insight into the direct and indirect energy inputs that need addressing to help agriculture become less energy-dependent. These input areas will be explained in this chapter and will reappear in Chapter Five, where each input area will be paired with energy principles that help form an energetic basis for farm design.

The Current Problems

Social Impacts

Relatively "cheap" fossil energy has replaced much human labor in the U.S. and in many other developed countries, enabling a large portion of the human population in these nations to enjoy a high standard of living (Pimentel and Pimentel 2008). This displacement of human labor has resulted also in mass migrations to cities and according to Wendell Berry, “a radical simplification of mind and of character” (Berry 1977, 44). In 1977, Berry projected that if no jobs are to be found in the cities, these unemployed farm workers may move into ghettos and become a drain on society instead of an asset. The incarcerated total for 2012 was 2,228,400, and the total population under the supervision of adult correctional systems was 6,937,600 (Glaze and Herberman 2013). The 1980 population of adults under correctional supervision was approximately 1,800,000 people (Glaze 2010). Though these statistics do not fully confirm Berry’s argument, the incarcerated population has more than tripled since 1980, and the population of agricultural workers has decreased from 3,364 in 1980 to 2,130 in 2013 (United States Department of Labor, “Labor Force Statistics from the Current Population Survey: Employment status of the civilian noninstitutional population, 1943 to date” 2014). Meanwhile, the urban population has increased from 73.7% in 1980 (United States Census Bureau, “Urban and Rural Population: 1900-1990” 1995) to 80.7% in 2012 (United States Census Bureau, “Growth in Urban Population Outpaces Rest of Nation, Census Bureau Reports” 2012), and rural communities are disintegrating under this “community-killing agriculture” that replaces people with machines (Berry 1977, 41).

As people move from small towns to cities, they become disconnected from their food source. The industrial food supply chain model goes like this: producer > processor > distribution > consumer, with each step generating its own share of waste (Gunders 2012). The second energy law requires that losses occur with every transformation, so each added step wastes energy, and sustaining this system necessitates large energy inputs. This system leaves farmers producing food for people hundreds of miles away (Pirog and Benjamin 2003) in a system dependent on fossil fuels, and leaving the consumers “agriculturally illiterate” with no connection—mentally, physically or emotionally to their food (Salatin 1995, 240). Fossil energy has allowed modern agriculture to become a centralized system, which encourages separation and ignorance between the farmer and the consumer (Salatin 1995). The disconnection from the food and the sacrifices made to produce it fosters ignorance and disrespect for it. In fact, in the U.S. 40% of the food produced goes uneaten, and 10% of the total U.S. energy budget is needed to get food from farms to tables (Gunders 2012). That is a lot of energy and a lot of uneaten food, especially in light of the 842 million malnourished people. Even in one of the world's most wealthy nations, one out of six Americans lacks a secure supply of food to their tables (Gunders 2012). This reinforces the notion that "people starve because of politics, not production" (Salatin 1995, 21). Politically and logistically issues exist, but public awareness and consumer behavior also play a role (Gunders 2012). However, the disconnection is not only on the behalf of the consumer but the farmer, too.

Joel Salatin, an activist farmer from Virginia, argues that the farmer is no longer connected to the community that their produce nourishes, and is "removed emotionally and mentally from the impact of his decisions" (1995, 241-2); these decisions may be regarding the quality of his food or perhaps the impacts of his farming methods on the local environment and public health. With all the emphasis on production and yields, the modern farmer has become a slave to agribusinesses, dependent on fertilizers, chemicals, and not least of all, subsidized energy. The health of the land and the quality of the food is sacrificed for financial profit.

For instance, proponents of the grain industry, which fed roughly 70% of grains to ruminates in the early 1990's (Salatin 1995), considers feeding grain to cattle efficient and profitable, though the cattle's inefficient metabolism produces fatty meat, known to cause obesity and cardiovascular health issues in humans (Smil 2008). Also, pesticides are another high energy input with adverse health affects. Pesticide use on food has ample evidence linking it to cancer, neurological defects, and respiratory and reproductive problems in humans (Pimentel and Pimentel 2008). Additionally, each year pesticide poisonings are responsible for three million hospitalizations, approximately 220,000 deaths, and 750,000 chronic illnesses (Hart and Pimentel 2002). These are just the negative side effects in people; pesticides also harm domestic animals and pollinators (Pimentel and Pimentel 2008). In addition to posing health hazards to people, industrial agriculture also creates health hazards in our ecosystems.

Ecological Impacts

In his book, *The Unsettling of America*, Wendell Berry wrote,

> "Contour plowing, crop rotation, and other conservation measures seem to have gone out of favor or fashion in official circles and are practiced less and less on the farm. This exclusive emphasis on production will accelerate the mechanization and chemicalization of farming, increase the price of land, increase overhead and operating costs, and thereby further diminish the farm population… The cost of this corporate totalitarianism in energy, land, and social disruption will be enormous… The fields lose their humus and porosity, become less retentive of water, depend more on pesticides, herbicides, and chemical fertilizers. Bigger tractors become necessary because the compacted soils are harder to work—and their greater weight further compacts the soil. More and bigger machines, more chemical and methodological shortcuts are needed because of the shortage of manpower on the farm—and the problems of overcrowding and unemployment increase in the cities." (1977, 10-11).

Berry summed up the social issues discussed previously in this paper, and listed several ecological issues that still cause major concerns: soil degradation, decreased water retention, and the need for chemical inputs. He also noted the economical issues that face farmers in terms of overhead and operating costs. Next, we will discuss the economics of modern agriculture, but first we will look at soil, water, nutrients, pollution, and fertilizers.

Modern agriculture is based on fossil energy—the tractors that plow the fields are fueled by subsidized fossil energy, and the actual plow or disk breaks up the soil structure and exposes loose soil to wind and rain energy. Tilled soil or soil with poor structure or low organic matter content is susceptible to erosion, which is intensified on greater slopes. Overgrazing or any other influence that leaves the ground bare also makes land more likely to erode. Erosion removes soil on the surface, as well as the nutrients that are bound to the soil particles, including the basic plant nutrients—nitrogen, phosphorus, potassium, and calcium (Pimentel et al. 1995). The water-holding capacity of the soil is impacted by erosion too, because less soil exists to hold the water and therefore runoff is increased. Additionally, soil biodiversity is reduced because of erosion. Without nutrients and water in the soil to nourish the crops, yields decline (Pimentel et al. 1995).

To replace and supplement the nutrients, synthetic fertilizer is often substituted. In 2000, Smil estimated production of industrial nitrogen to be 80 Mt per year (Smil 2000). The energy cost of 80 Mt is 40 GJ/t N; 40% of 40 GJ/t N is process energy and 60% is feedstock. Furthermore, urea, the leading solid nitrogen fertilizer requires an extra 25 GJ/t N to manufacture (Smil 2000). These numbers reinforce that the practice of using synthetic nitrogen fertilizer requires a lot of energy upstream, before ever reaching the farm. If not carefully applied on the land, fertilizers (synthetic and organic) can leach into ground water, runoff in rivers and streams, and volatilize, becoming an agent of pollution and an economic loss to the farmer.

In addition, phosphorus, a main nutrient required for plant growth, is predicted to peak by 2040, when demand will exceed supply (Cordell and White 2013). Phosphorus cannot be manufactured synthetically, but can only be harvested from non-renewable phosphate rock, mostly located and controlled by a few countries: Morocco, Iraq, China, Algeria, and Syria (Cordell and White 2013). The stores are mined, treated with sulfuric or phosphoric acid (Smil 2000), transported, and spread over agricultural land. Once crops are eaten, the phosphorus leaves human bodies in urine and feces and treated as waste, being pumped to a wastewater treatment plant for treatment with chemicals before being distributed to oceans, rivers, or on land. Recovery is not the current trend, though this must change to continue producing food past 2040 (Cordell and White 2013). The amount of phosphorus lost and the related energetic costs are shown in Table 3.1. Also shown in this figure is water runoff—another important, and often limiting, factor in agriculture.

Water, a vital part of any type of agriculture, is a valuable resource. Crops demand lots of water to grow and insufficient water stunts growth (Pimentel et al. 1995). In *Feeding the World*, Smil (2000) presents calculations to show that fresh water resources for human use are becoming increasingly subjected to supply stress. The current trends of urbanization, electrification, industrialization, and expanded cropping are further increasing the demand (Smil 2000). Water pollution, a result of many of these trends, concurrently impacts the supply. Yet, water is a relatively cheap resource at present, and is mistreated and misused as a result.

Collectively, the losses associated with erosion result in huge external inputs to offset the factors (Pimentel et al. 1995). Pimentel et al. (1995) estimated that on-site and off-site impacts of soil erosion and associated runoff require additional energy inputs of 1.6 X 10^6 kcal of fossil energy per hectare per year (647,500 kcal per acre per year). The energetic costs of soil erosion from the study by Pimentel et al. (1995) are shown in Table 3.1.

Table 3.1. The Estimated Annual Economic and Energetic Costs per Hectare of Soil and Water Loss from Conventional Corn. Assumptions: water and wind erosion rate of 17 tons/ha/year over 20 years (Pimentel et al. 1995).

Factors	Annual quantities lost	Cost of replacement dollars	Energetic costs (10^3 kcal)	Yield loss after 20 years of erosion (%)
Water runoff	75 mm	30	700	7
Nitrogen	50 kg		500	
Phosphorus	2 kg	100	3	8
Potassium	410 kg		260	
Soil depth	1.4 mm	16	-	7
Organic matter	2 tons	-	-	4
Water holding capacity	0.1 mm	-	-	2
Soil biota	-	-	-	1
Total on-site		146	1460	20
Total off-site		50	100	
Grand total		196	1560	

The on-site costs, as explained by Pimentel et al. (1995), involve the inappropriate agricultural practices that result in nutrient and water loss from farms, which incur the economic and environmental on-site costs to farmers. However, as the eroded soil and the particles attached to it invade nearby streams, damages also result off-site. Off-site issues include roadway, sewer and basement siltation, drainage disruption, undermining of foundations and pavements, gullying of roads, earth dam failures, flooding, eutrophication, siltation of harbors and channels, loss of wildlife habitat and disruption of stream ecology and increased water treatment costs (Gray and Leiser 1982). The impacts to water systems are the most serious—harm is done to aquatic flora and fauna as the agricultural runoff contaminates the water with soil particles, fertilizers, and pesticide chemicals (Clark 1987).

To combat erosion, organic matter is used to help cover the soil, protecting it from wind and water flows. Conservation tillage has become more common among conventional farmers in recent years. For example, the residues of monocultures are mulched and left as organic matter to protect the soil. Organic matter has numerous benefits: it improves soil structure; increases aeration; increases the water holding capacity of the soil and decreases evaporation, runoff, and erosion; buffers against pH changes in the soil; increases the cation and anion exchange capacities of the soil; constantly releases nutrients to be used by the crops; and supplies energy to soil fauna and microorganisms that are responsible for the mineralization of the plant nutrients and improved physical and chemical attributes of the soil (Allison 1973; Pimentel and Pimentel 2008). To take away these ecosystem services provided by organic matter requires more energy input into agricultural systems (Pimentel and Pimentel 2008). Still, many conventional farmers still do not understand the role of organic matter and therefore do not practice conservation tillage in their fields of monocultures.

Monocultures are another issue with modern agriculture. Planting one single crop over large areas of land decreases the biodiversity that would exist there naturally. To disrupt nature's complex ecosystem and replace it with one or two crops requires large amounts of energy (Pimentel and Pimentel 2008). Additionally, one large population of a particular species attracts large populations of pests and plant pathogens that are attracted to that species. Also, the bare ground around the stand of the monoculture allows weeds the opportunity to invade. To fight the pests and weeds, more energy is needed to produce, transport, and apply pesticide and herbicide chemicals (Pimentel and Pimentel 2008).

Energy has also been spent developing crop varieties that are resistant to these herbicides. Additionally, genetic breeding and biotechnology has eliminated the protective and survival mechanisms of many plants and animals so that the most food possible can contribute to net growth (Odum 2007). These varieties are dependent on industrial agricultural practices. For genetically similar animals concentrated on the land, the risk of epidemic disease is increased. An example is the hoof and mouth disease outbreak in 2001 (Odum 2007). In a world without fossil energy, a lack of diversity in genetics is a threat to resilience and survival. Figure 3.1 from Odum (2007) compares the energy needs of cattle not dependent and dependent on fossil energy.

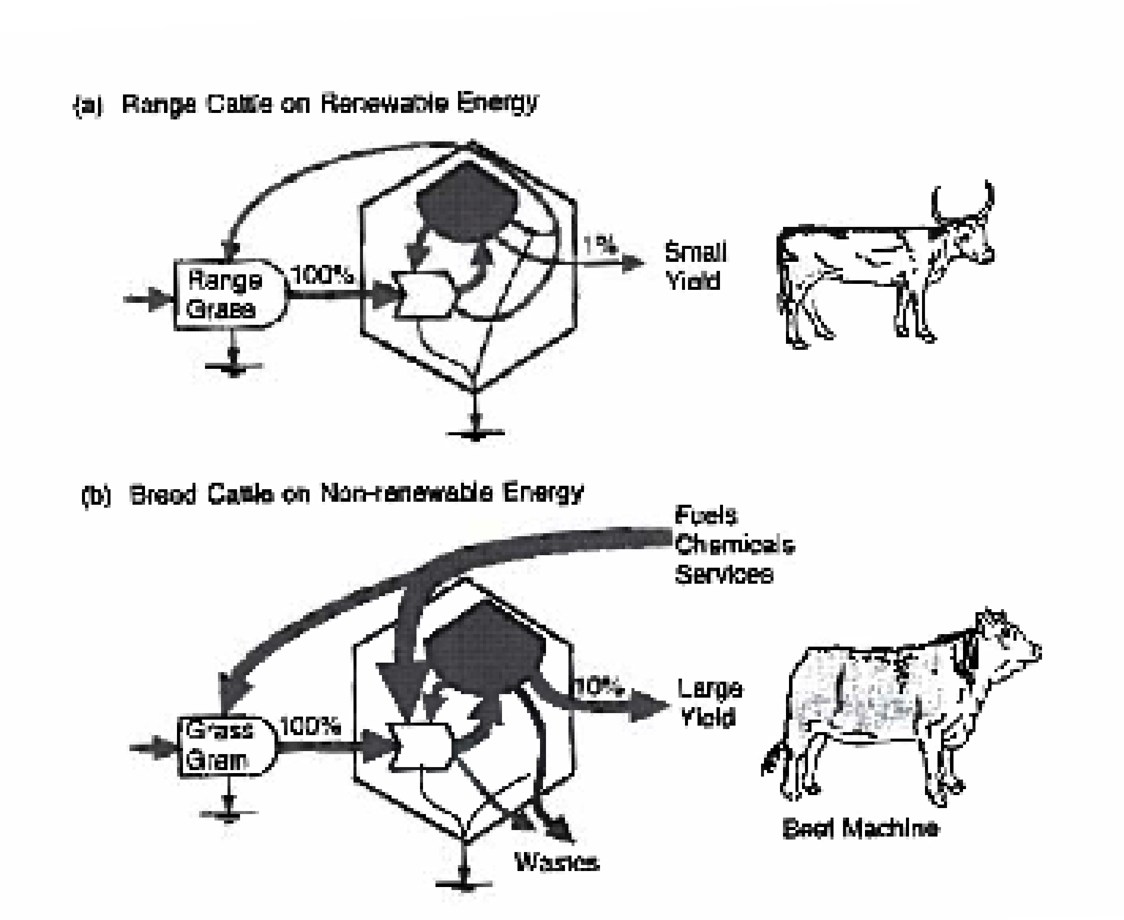

Figure 3.1. Self-sufficient Animals Versus Animals Requiring Large Fossil Inputs (Odum 2007, 194).

Animal pasture-based operations make use of the animal wastes by rotating the animals from paddock to paddock, spreading their wastes to the benefit of the land. But, in feedlots spotted all over the Midwest, the situation is very different. Feedlot animals are concentrated in an area and fed grain. The grain-fed model takes animals out of fields where they originally harvested their own food. Instead, the farmer works to feed them by growing, harvesting, and delivering the grain to the cattle. The farmer is using “cheap” fossil fuels to do the work for the cow, which ties the price of beef to the price of oil. In feedlots, such a high concentration of animals turns nutrients into wastes.

The situation is similar for confined dairy cows, chickens, and pigs that are fed food produced with subsidized energy. In addition to the environmental harm, disease, and dependency on antibiotics, many people dislike this confinement model due to concerns for animal welfare. Still others may see it as an ethical dilemma when animals are fed crops suitable for human consumption or grown on land that could be producing food for humans (Smil 2000).

Energetically, "eating closer to the Sun" supports a larger population due to the second energy law, which ensures energy losses with an additional transformation. However, humans and animals are not always in competition for food. Cattle, sheep, and goats that graze on semi-arid grasslands, sloped terrain, and mountain meadows are not competing with human food production because this land should never be converted to cropland (Smil 2000). Animals can also graze on leguminous cover crops in a garden rotation. Animals can utilize phytomass that is unsuitable for humans and provide meat, eggs, and milk for human consumption. When managed properly, even their wastes benefit humans by recycling nutrients and improving soil quality (Smil 2000).

These are just a few of the social and ecological issues that have resulted from the industrialization of agriculture. Many more exist, and there are likely some of which we are still unaware. The issues are complex and interrelated. Because of the segmented, simple approach toward managing a complex system, actions in one area affect the rest of the system, often with little understanding of the long-term effects on that system. The next section will analyze agricultural operations to better understand the energy inputs. The inputs from the studies will be classified and analyzed with respect to the energy laws to develop the energy-based design guidelines.

Energy Analyses of Agricultural Systems

This section gives an overview of agricultural EROIs. For the most part, the energy inputs into these studies include the direct and indirect inputs—up to a certain point. As Odum points out, “Much of the power flow that supports intensive agriculture is not used on the farm but is spent in the cities to manufacture chemicals, build tractors, develop varieties, make fertilizers, and provide input and output marketing systems, which in turn maintain mobs of administrators and clerks who hold the system together” (190). Regardless, these EROIs provide a starting point for understanding the role of energy in agriculture, and they are becoming more accurate as the science improves. Below, a study by Pimentel et al. (2008) is reviewed, followed by an in-depth analysis of a diversified organic vegetable farm.

Study by Pimentel et al. 2008 - Energy Inputs in Food Production

Pimentel et al., (2008) performed an energy study including 20 cropping systems in developed and developing countries. Labor was a large input in developing countries, and mechanization and fertilizers contributed a large amount of energy in the developed countries. Large disparities exist between the developing and developed countries in terms of inputs and outputs. Pimentel et al. (2008) note that grain production per area increased four-fold during the Green Revolution, but in the two decades before 2002, the yields had been in decline, despite technologies (Pimentel et al. 2008). Rice, corn, wheat, soybeans, cassava, potato, sweet potato and cabbage were analyzed in the study because they provide most of the world’s food supply.

Apples, oranges and tomatoes were included because of the minerals and vitamins they contain (140). However, the breakdown of inputs is not given for each crop. Also, the energy inputs and outputs given in this study are based on averages for individual crops, not detailed studies of specific farms. The methodology for this study is not very detailed either, and many values are based on averages. For instance, the study states, "no attempt was made to rate and identify the amount of liquid fuel (oil) used in each cropping system" (140). Also acknowledged are the difficulties in assessing the energy inputs for the machinery and labor. Still, the values give an idea of agriculture's dependence on fossil energy and the yields made possible by fossil energy based on the EROI methodologies from 2002.

Due to the importance of corn in U.S. agriculture, corn energy inputs for the U.S. based on this study are included in Table 3.2. Today, continuous corn monocultures require more insecticides than any other crop in the U.S. (Pimentel and Pimentel 2008). Odum (2007) developed an emergy evaluation of intensive corn agriculture after a study by Pimentel and Hall from 1984. Odum's diagram is shown in Figure 3.2. Also included is Table 3.3, which covers various crops in different countries according to Pimentel et al. (2008).

Table 3.2. Energy in Corn Production in the United States (Pimentel et al. 2008, 142).

Energy Inputs and Costs of Corn Production per Hectare in the United States			
Inputs	**Quantity**	**k cal x 1000**	**Costs ($)**
Labor	11.4 h	462	$114.00
Machinery	55 kg	1018	$103.21
Diesel	42.2 L	481	$8.87
Gasoline	32.4 L	328	$9.40
Nitrogen	144.6 kg	2688	$89.65
Phosphorus	62.8 kg	260	$34.54
Potassium	54.9 kg	179	$17.02
Lime	699 kg	220	$139.80
Seeds	21 kg	520	$74.81
Irrigation	33.7 cm	320	$123.00
Herbicides	3.2 kg	320	$64.00
Insecticides	0.92 kg	92	$18.40
Electricity	13.2 kWh	34	$2.38
Transportation	151 kg	125	$45.30
Total	7965 kg yield	7047	$844.38
kcal input:output = 1:4.07			

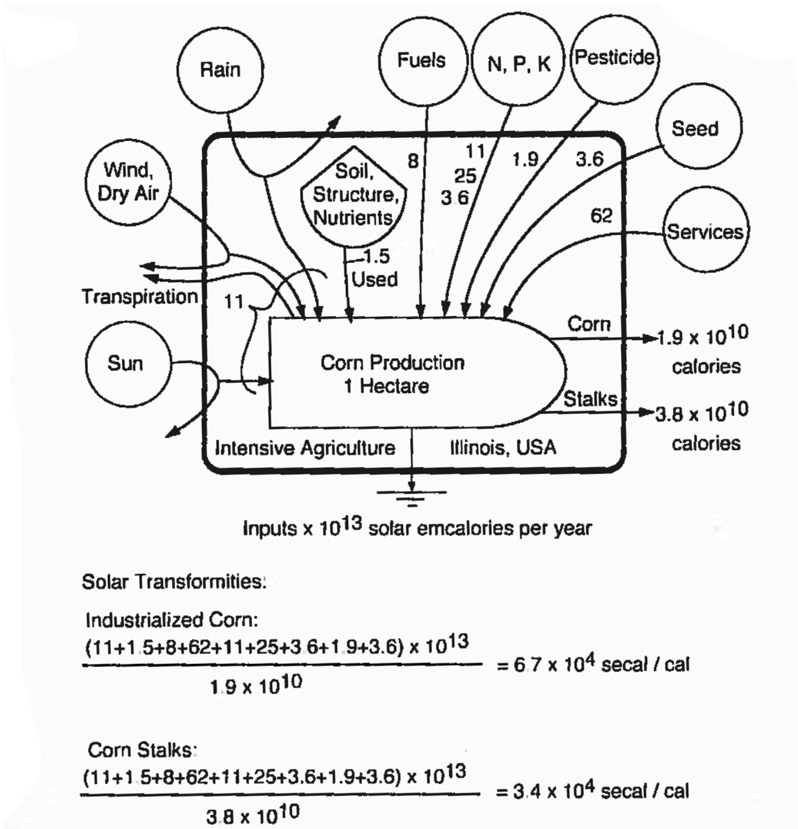

Figure 3.2. Energy Inputs and Outputs in Intensive Corn Production (Odum 2007, 189).

Table 3.3. Energy and Economic Costs of Various Crops in Developing and Developed Countries. Economic data was used from each country, and the economies of these countries differ significantly. This should be considered regarding the economic data (Pimentel et al. 2008, 150).

Energy and Economic Costs of Various Crops Produced in Several Developing and Developed Countries (per hectare)			
Crop	**Country**	**Economic Costs ($)**	**kcal input:output**
Soybean	Philippines	310.58	1:1.47
Potato	Philippines	655.60	1:0.42
Sweet Potato	Vietnam	908.73	1:2.01
Cabbage	United States	1,341.08	1:1.76
Cabbage	India	206.95	1:0.53
Tomato	United States	7,337.42	1:0.34
Tomato	Pakistan	1,746.73	1:0.94
Orange	United States	3,048.55	1:1.03
Apple	United States	7,724.53	1:0.61
Apple	India	81.29	1:1.55
Corn, irrigated	United States	1,674.88	1:1.07

An Organic Vegetable Farm in Kentucky, USA

The next study we will examine was conducted on a 2.51 ha (6.2 ac) diversified organic vegetable farm in Lexington, Kentucky by Schramski et. al (2013). Schramski, et al. (2013) suggest using energy as a measure for USDA organic operations in a study of the University of Kentucky diversified organic vegetable farm that markets through a Community Supported Agriculture (CSA) model. The rationale is, "We consider that a one-for-one relationship of energy inputs to outputs, which exists in self-regulating ecosystems, provides a goal for sustainable and organic production and is a holistic, systems-level indicator of the sustainability of agricultural production systems (i.e. EROI>=1)" (Schramski et al. 2013, 102). Using current state-of-the-art input-output energy analysis, Schramski, et al., provides results that indicate agriculture indeed consumes more energy than it produces.

Energy accounting is complex. For their study, Schramski, et al. (2013) use a generalized EROI methodology similar to others for food production systems, and include all direct and indirect (i.e. embodied energy) energies “practically possible,” including fossil fuels. This is the intent of an EROI ratio—to understand all the upstream energy required to produce a product or good. It is founded on the “first law of thermodynamic energetics where solar shortwave energy-in equals thermal long-wave energy-out plus any chemical energy accumulation” (Schramski, et al. 2013). Schramski, et al. (2013) adhered to common convention by not including a quantity for insolation—the assumption is that the food grown is eaten or decays, thereby becoming ultimately reduced to long-wave thermal radiation. This assumption accounts “for both the solar shortwave radiation input to our model and the corresponding and inevitable long-wave thermal radiation out,” which the first law of thermodynamics ensures is equal (103). The system boundary is the perimeter of the farm, and all energy and mass crossing the boundary are included in the analysis (Schramski et al. 2013).

This analysis categorized inputs based upon whether they were used directly on the farm (i.e. direct inputs) or were indirect inputs, which accounted for energy required upstream that enabled those goods and products to get to and be used on the farm. These input categories will be used in Chapter Five of this research to understand the influence the design guidelines may have on inputs into an agricultural system. The next two paragraphs provide details on the inputs, followed by a section on how the calculations were made.

Included in direct energy inputs are labor, fuels, and electricity and natural gas (Schramski et al. 2013). The direct labor input is an estimate of the human labor energy expended on the farm. The direct fuel input was the amount of diesel and gasoline that was consumed by the tractors on the farm. The direct electricity and natural gas included the amount of electricity and natural gas used in two buildings that support the CSA and the greenhouse. Some of this energy went to power refrigerators, a stove, lights, a coffee pot, a window unit, a workshop with basic hand tools, and ventilation fans (Schramski et al. 2013).

The indirect energy inputs include compost, gasoline and diesel, plastic mulch (materials), fertilizer, irrigation, pesticides, machinery, seed, electricity, natural gas, and labor (Schramski et al. 2013). The indirect energy input for the compost is based on an estimate of the energy required to process the compost at the commercial-scale, high-turning compost facility in the neighboring county by the Kentucky farm. The indirect gasoline and diesel energy accounts for the energy required to extract and refine the liquid fuels used on the farm. The indirect plastic mulch material input is an estimate of the amount of energy required to produce the low-density polyethylene film. The indirect fertilizer inputs stemmed from the indirect energy required to make the supplemental fertilizer the farm used. The fertilizer is 5-4-3 (N-P-K) certified organic fertilizer derived from pastured broiler chicken litter, which was applied at 60 lb. nitrogen (N) per acre. The indirect energy for irrigation covered the energy required to treat the water used for irrigation, as the farm is in an urbanized area with a municipal water supply. Indirect energy for the biopesticides used on the farm was estimated from the amount of energy it takes to manufacture, formulate, package, and transport the pesticides. Upstream energy to manufacture the machinery was included in the indirect machinery value. Indirect energy for seed is an estimate of the energy required in seed production. Electricity also has indirect costs associated with mining, transporting, and thermal losses for converting coal to electricity; the indirect value for electricity accounted for the upstream energy required to generate the amount of direct electricity that was used on the farm. The same with natural gas—the indirect energy input value for natural gas is based on the energy to supply the amount used to the farm. The indirect labor input calculated pertains to the energy input needed to sustain the human laborers working on the farm. For each of these inputs, calculations were made to estimate the energy input each contributed to the system (Schramski et al. 2013). These calculations are further described below.

For the UK farm study, many records were kept to measure the direct inputs. The factorial method was used for measuring labor energy expenditures, accounting for type and duration of activities. For fuels, a log was kept and the Nebraska Tractor Data conversions were employed based on the fuel type. The electricity and natural gas supporting the two CSA and one greenhouse was measured by electric and gas meters (Schramski et al. 2013).

Calculating the indirect energy inputs are the most difficult for this type of analysis. Indirect inputs vary and are site specific. Compost was estimated based on studies that are most similar to the compost operation at the UK farm. Indirect energy required for gasoline and diesel was adopted from a 1992 study. The plastic mulch energy values vary widely, but the trends shown in the studies are downward, so a lower value was used for the analysis. The fertilizer values are from other studies as well, with the embodied energy of 30.15 MJ/kg being the estimate to produce an organic 5-4-3 fertilizer; this value is 14 MJ/kg lower than Smil's value for synthetic nitrogen production. Irrigation was from a municipal distribution system, which requires less energy than many agricultural operations that use pumps. Values from a study done in 2000 were used for irrigation estimates. Organic pesticide data is not well known, and Schramski et al. (2013) opted for a conservative approximation for the embodied energy required to process and transport the biopesticides to the farm that is based off of low values for the synthetic counterpart. The values for the farm machinery were numbers from Smil et al., 1983, with considerations for an 8% increase for repairs and a 12-year amortized depreciated life for the equipment. An average of 16.7 MJ/kg was derived from a study for the embodied energy of the seed. Indirect energy needed for electricity includes mining and transporting the fuel and heat losses. Coal is the predominate source for power plants in Kentucky, and calculations considered the 33% efficiency of converting coal to electricity. As it is not well-researched, indirect energy associated with natural gas was conservatively estimated to have an upstream energy requirement of 10%, which was added to the natural gas consumption on the UK farm. For indirect labor estimates, calculations were based on BMR and thermoregulation needs, leaving 20% for physical activity; a factor of 19.4 was used to determine the indirect energy needed for the labor output. This is a summary of the direct and indirect energy inputs.

All output weight estimates were based on a sample of the weekly bundles, of which an average was used. According to Schramski et al. (2013), the weights for the products “were then converted to the Caloric content using the USDA (2011) nutrient database” (107). A more in-depth explanation of these estimates is detailed in “Energy as a potential systems-level indicator of sustainability in organic agriculture: Case study model of a diversified, organic vegetable production system,” from which all of the previous information on direct and indirect inputs is derived.

Despite all the estimates and problematic issues with energy accounting, the results of the Schramski et al. (2013) study are important for assessing agriculture’s dependence on fossil energy and ultimately, its sustainability. Table 3.4 details the results. The 40:1 input-to-output ratio is a large disparity from what natural ecosystems function within.

Table 3.4. Results of UK farm study (Schramski et al. 2013, 107).

University of Kentucky organic vegetable CSA direct and indirect input energy distributions in mega joules (MJ) for the 2011 season.

Direct inputs	
Human labor	4592
Liquid fuels	85,210
Electricity	115,992
Natural gas	508,401
Total	714,194
Indirect inputs	
Pesticides	1808
Irrigation	1965
Seed	5010
Natural gas	45,317
Materials	48,685
Machinery	88,868
Human labor	89,078
Liquid fuels	98,969
Fertilizer	165,339
Electricity	265,376
Compost	472,317
Total	1,282,734
Total input	1,996,928
Total output	50,391
Input–output energy ratio	40–1

The study also mentions that the authors are unaware of any agricultural EROI studies that include all the categories that they did in the indirect energy analysis—a potential source of the larger input-output gap. In addition, the pedagogical nature of the farm may increase inputs, especially in regards human labor, which amounts to 7% (direct and indirect) of the total inputs. Another possible deviation from other diversified organic vegetable farms comes from the outreach and extension focus of the CSA to farmers converting from mechanically intensive monoculture systems; the methods at the farm (i.e. mechanical equipment, purchased fertilizers, pesticides, etc.) are such that the farmers are familiar with them (Schramski et al. 2013).

Input Categories

Based on the categorization of inputs from the above studies, a table was developed with all of the inputs listed. Also included are inputs from two other studies: Pimentel 2006 and Baum et al. 2009. These studies were omitted from the discussion above for different reasons. Pimentel 2006 was very similar to the Pimentel et al. 2008 studies presented, with the exception that fungicides were an additional input for tomato production. The study by Baum et al. 2009 was not included because it is not representative of modern agriculture though the inputs listed are inclusive.

After listing the inputs, based on the type, each input was reclassified into broader categories with the goal of accounting for all types of inputs on a conventional or organic farm. The result of the grouping is below in Table 3.5.

Table 3.5. Categorization of Energy Inputs. Note: Because one list does not contain a category does not mean it was not accounted for, only that it may have been categorized differently.

Energy Inputs from Various Agricultural Studies				
Pimentel (2006) - Tomatoes	**Pimentel et al. (2008) - Corn**	**Baum et al. (2009) - Sunshine Farm**	**Schramski et al. (2013) - Diversified Vegetable CSA**	**Input Categories**
Labor	Labor	Labor	Labor - D	Labor
Machinery	Machinery		Machinery - ID	Machinery
Diesel	Diesel	Diesel	Fuels - D	Fuels
Gasoline	Gasoline	Gasoline		Fuels
Nitrogen	Nitrogen		Fertilizer - ID	Fertilizers
Phosphorus	Phosphorus			Fertilizers
Potassium	Potassium			Fertilizers
Limestone	Limestone			Amendments
Seedlings	Seeds	Seeds	Seed - ID	Seeds
Irrigation	Irrigation		Irrigation - ID	Irrigation
Insecticides	Insecticides		Pesticides - ID	Chemicals
Herbicides	Herbicides			Chemicals
Fungicides				Chemicals
Electricity	Electricity	Electricity	Electricity, nat. gas - D	Electricity
Transportation	Transportation			(Falls under other categories)
		Materials	Materials - ID	Materials
		Biodiesel		Fuels
		Feed		Feed
		Animals		Animals
		Electronics		(not classified)
		PV cells		(not classified)
		Medicine		Medicine
			Gas and diesel - ID	Fuels
			Compost - ID	Amendments
			Electricity, nat. gas - ID	Electricity
			Labor - ID	Labor

Table 3.6 is a list of the categorized inputs. Because this research will not be making any calculations, indirect and direct inputs have not been differentiated. It is assumed that impacts to any direct inputs will inevitably impact the associated indirect energy as well. For instance, more direct human labor will require more indirect inputs for human labor. Likewise, decreasing the amount of direct fuels used will decrease the indirect upstream energy needed to acquire and transport them. Also, animals from the Baum et al. (2009) study are classified, but are not considered in the input categories because they are considered a store of biological energy for this research and not an energetic input. Instead, they are considered a necessary part of an agricultural system.

Table 3.6. Final List of Input Categories.

Input Categories
Labor
Machinery
Fuels
Fertilizers
Amendments
Seeds
Irrigation
Chemicals
Electricity
Materials
Feed
Medicine

This chapter provides an overview of some of the big social and ecological issues in modern agriculture. Despite the uncertainties in energy accounting, the energy analyses presented are evidence that fossil energy is needed for modern agricultural production. As

Schramski et al. (2013) pointed out, present-day agricultural production is operating outside of our energetic means, and therefore our food supply is dependent on fossil energy. The inputs from each study provide elements of agricultural systems that the guidelines aim to reduce. The next chapter studies traditional agricultural societies to understand the treatment of the landscape and the methods of management used to produce food without fossil energy, in order to develop design guidelines that will reduce the inputs listed in this chapter.

CHAPTER 4

ENERGY IN THE HISTORY OF AGRICULTURE

Following the second law of thermodynamics, which indicates that systems gravitate toward thermodynamic equilibrium via an increase in entropy, agricultural systems have always trended towards disorder, in need of human intervention to maintain order and workability through energy expenditures. Before agriculture, people hunted and gathered their food. This chapter reviews the methods societies employed to provide food before and after industrialization. Also included are precedent studies of various societies throughout the world.

Preindustrial Provisioning

In early societies, foraging (hunting and gathering) was the subsistence pattern that existed before farming. Foraging supported population densities in the range of 0.01-0.9 people/km^2, as shown in Figure 4.1 (Smil 2008, 149). These hunting and gathering societies searched and brought fruits, nuts, vegetables, and seeds, including grains, and other food from the natural local ecosystem back to camp for themselves, the younger children, and older members of the camp to consume. Eventually, associations were made between the seeds that were dropped at the camps and the concentrated growth of crops discovered upon a return to the camps (Pimentel and Pimentel 2008). Less energy and work was needed to harvest the concentrated vegetation compared to randomly gathering food in nature; hence food cultivation began (Pimentel and Pimentel 2008). Another factor in the gradual switch to farming was the population growth that pushed the limits of foraging and promoted the adoption of a more productive subsistence (Smil 2008).

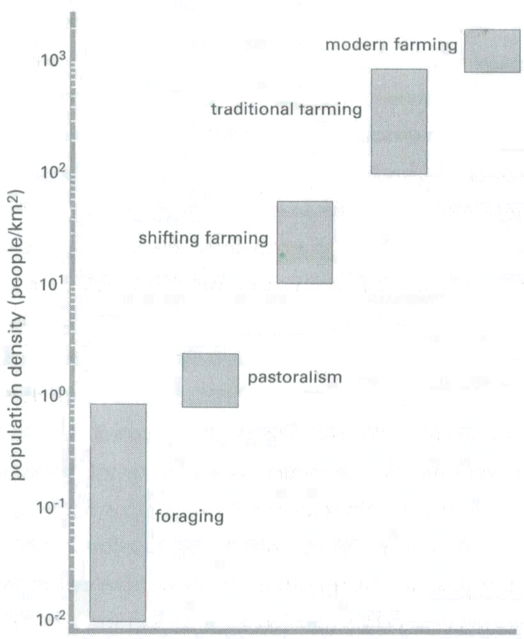

Figure 4.1. Food Provision Methods and the Various Population Densities that Each Supported in Preindustrial Times (Smil 2008, 149).

Before delving into early agricultural societies, the energetics of a hunter-gatherer society will be discussed. The first precedent study presented is the !Kung bushmen of Botswana, Africa—presently a hunter-gatherer society living in an arid landscape. The societies reviewed in the precedent studies inhabit different landscapes in various continents to provide a range of environmental conditions in which these societies survived, or in the case of the !Kung bushmen—survive.

Precedent Study: !Kung bushmen in the Dobe area of Botswana, Africa

The !Kung bushmen presently inhabit the Dobe area of Botswana, in the south-central part of Africa. In the arid land of the !Kung bushman, permanent watering holes exist only where limestone strata has been exposed, making water the major limiting factor for the tribe. This influences where the bushmen locate their camps because they must be able to access food and water easily. At the time of the study, the bushmen's diet, by weight, consisted of 33% mongongo nuts, 37% meat and 30% miscellaneous plant foods (Lee 1969) which totaled approximately 2,140 kcal/day. Over half of the calories were supplied by the mongongo nuts, which accounted for 1,200 kcal/day. The population density of the bushmen was 10.4 km^2, or 2,570 acres per person (Lee 1969).

The bushmen sited their camps close to water and collected desirable food from around the camp until the available food in the area was exhausted. Lee (1969) noted that the camps are often in nut forests, and during the first week the area within a 1.6 km (1 mi) radius of the camp is depleted of nuts. After the second week the area within a 3.2 km (2 mi) radius is exhausted, and after the third week, likewise, the supply is diminished within a 4.8 km (3 mi) radius. As the second law of thermodynamics guarantees, the amount of energy required for collecting food increases as the bushmen travel farther from camp. The cost curve gradually increases as the distance grows from 3 to 19 km (1.9 to 11.8 mi) round trips. A 2-day round trip is necessary for any distance over 19 km, and the energy cost is greatly increased due to the water and other loads that the bushmen must carry for the overnight trip (Pimentel and Pimentel 2008).

During the dry season, the bushmen ate less desirable foods closer to camp to avoid long trips with high energy costs. Lee (1969) reported that often the older, less mobile members would stay closer to camp and gather the less desirable foods, while the younger members made the longer trips. Conversely, the rainy season brought temporary water pools, allowing camps to be sited within close proximity to nuts and water. Round trips were rarely more than 9.7 km (6 mi) during the rainy season.

The tables below from Pimentel and Pimentel (2008) show energy inputs and outputs for two different scenarios; the first is the energy analysis for the bushmen gathering nuts 4.8 km from camp (Table 4.1) and the second is the energy analysis for the bushmen gathering nuts 9.6 km from camp (Table 4.2). These tables are based on information from Lee (1969).

Table 4.1. Input-Output of !Kung Bushmen Gathering at 4.8 km (Pimentel and Pimentel 2008, 50).

Input-Output Analysis of !Kung Bushmen Gathering Nuts 4.8 km from Camp		
	h	kcal
Inputs		
Travel to nuts	1.2	270
Collecting nuts	3	675
Return trip (carrying 12.5 kg of nuts)	1.2	462
Subtotal		1,407
Sleep	10.5	473
Other activities	8	800
Total	24	2,680
Outputs		
Shelled nuts, 1.75 kg		10,500
Output:input ratio		3.9:1

Table 4.2. Input-Output of !Kung Bushmen Gathering at 9.6 km (Pimentel and Pimentel 2008, 51).

Input-Output Analysis of !Kung Bushmen Gathering Nuts 9.6 km from Camp		
	h	kcal
Inputs		
Travel to nuts	2.4	540
Collecting nuts	3	675
Return trip (carrying 12.5 kg of nuts)	2.4	924
Subtotal		2,139
Sleep	10.5	473
Other activities	8	600
Total	24	3,212
Outputs		
Shelled nuts, 1.75 kg		10,500
Output:input ratio		3.3:1

The tables above show that more time and energy is required for traveling longer distances. Correspondingly, the output/input ratio declines as the distance traveled from camp increases. These values are based on data showing that women collect 2.2 days/week and gather 23,100 kcal/week. This resulted in enough food for the gatherer and approximately 38% surplus. The extra contributed to the diet of the elderly and children who made up almost one-third of the population (Pimentel and Pimentel 2008). The hunters and gatherers spent an estimated 2.2 days/week obtaining food, with 4.8 days/week spent on other activities such as gathering firewood, moving to new camps, constructing shelters and making clothing, caring for children and having leisure time (Lee 1969).

The study of the bushmen exhibits responses to the energy laws. The camps were the spatial centers, and the distances they traveled represent the human scale for their method of food provision. Without subsidized energy, they were unable to expand beyond their human limits.

This also means that they did not concentrate humans or materials to an extent that incurred excessive energy costs. Also of note are the variation in the camp locations and behaviors of the society. These are both a direct response to their environment—changing with the seasons and stresses.

Though the bushmen are a hunting and gathering society, we can still learn much from their methods of obtaining food. Next, we will explore the energetics of early agriculture.

Early Agriculture

Between 5,000 to 10,000 years ago, agriculture emerged independently in at least seven locations on three continents (Smil 2008). A critical stage of early agriculture was clearing natural vegetation to minimize competition for water and nutrients for crops. Burning was often employed to remove weeds and add nutrients to the soil (Pimentel and Pimentel 2008; Smil 2008). Seeds were planted with digging sticks; the harvest found upon a return to the site also helped to feed the local living things: mammals, birds, insects, and disease organisms (Pimentel and Pimentel 2008). Eventually, the camps became more permanent because the needed food was produced nearby, and people no longer needed to travel to find food. Early camps were abandoned every one to three years because of nutrient deficiencies in the plots and other problems, such as pest outbreaks. After 10 to 20 years of the land lying fallow, people would return (Pimentel and Pimentel 2008; Smil 2008). This type of cultivation is referred to as shifting, swidden, or slash-and-burn agriculture. Shifting farming could support approximately 10-60 people/km^2, but at the cost of higher energy inputs (compared to hunting and gathering), which were initially provided by human labor (Smil 2008). Smil (2008) noted that shifting agriculture was once widespread on every continent except Australia.

Living in close proximity of the food source, and caring for the crops promoted "ownership" of the land (Pimentel and Pimentel 2008; Smil 2008), and protection of the crops from other competition from mammals, birds, or other pests (Pimentel and Pimentel 2008). Culturally, crop cultivation fostered socialization also, which was a desirable goal for the human species as societies evolved (Smil 2008). Energetically, shifting cultivation had energy returns ranging from 11- to 15-fold for small grains, 20- to 40-fold for most roots crops, bananas, and high corn yields, and almost 70-fold for some exceptional roots and legumes that were well-located, with varying labor inputs between 600h/ha and 3200h/ha (Smil 2008). Figure 4.2 is an energy diagram for shifting agriculture.

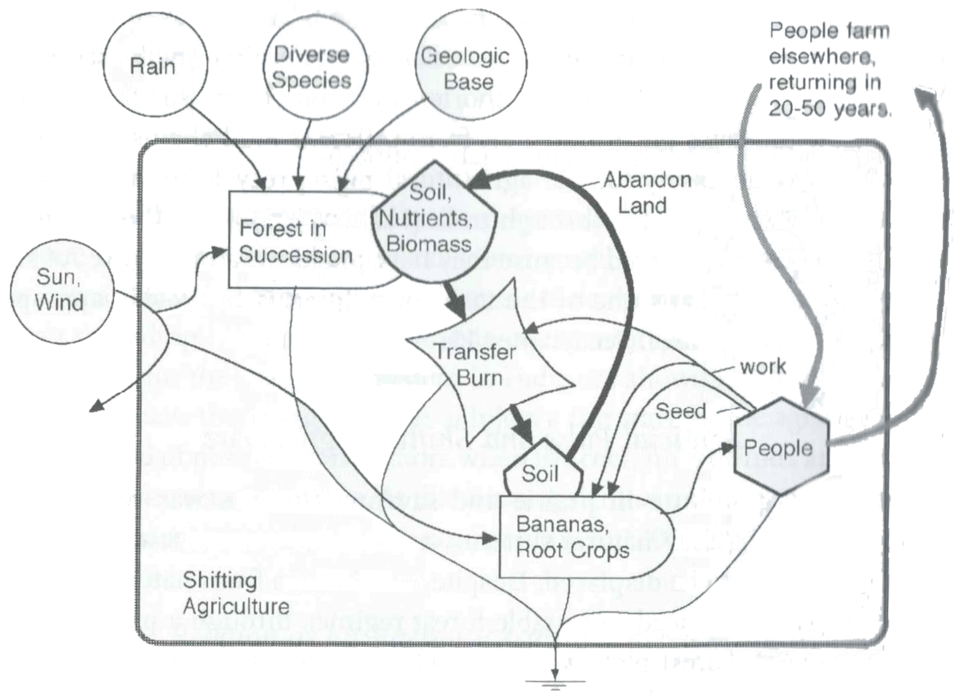

Figure 4.2. Energy Systems Diagram for Shifting Agriculture. This is an example of an energy system in which accumulated forest emergy is utilized for food crops for several years. Then, nutrient deficiencies, poor soil structure, insects and weeds force the agriculturalists to move on. Later, the cycle is repeated. The thick lines indicate the cycles of soil and people (Odum 2007, 186).

Over time, intensification of farming increased to support a larger population (Pimentel and Pimentel 2008; Smil 2008), though Smil (2008) pointed out that a natural tendency existed to postpone the adoption of a more intensive arrangement as long as a less intensive system would suffice. Figure 4.3 shows energy system diagrams of a hunting and gathering based ecosystem compared to a renewable agriculture, or agroecosystem. Energy demands increase as intensification increases, and advances are made in stages, from long forest fallow (one or two crops with 15-20 years of rest); to bush fallow (four to six crops with four to six year breaks with only time for bushes to reemerge); to short fallow (one or two crops followed by a year break); and regular annual cropping (fall and winter rests); to multicropping (often with irrigation, with two to three grain or oil crops followed with five to six vegetable crops planted successively) (Smil 2008). Each advance captures more of the site's solar energy through photosynthesis and supports a higher population density, estimated from 100 to 1,000 people/km^2 for traditional agriculture, as seen in Figure 4.1 (Smil 2008, 149). The additional energy needed requires that members of the society contribute to the work. Also, more energy is spent clearing, planting, cultivating, irrigating, and making tools, as well as more long-term investments such as terracing, irrigation systems, and roads.

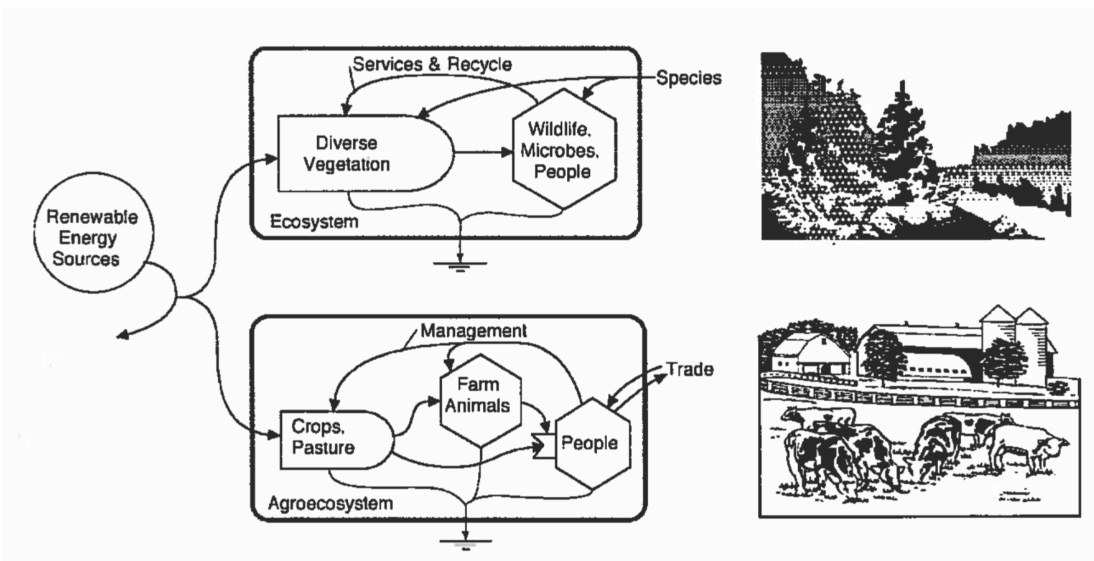

Figure 4.3. Energy Systems Diagrams for Hunting and Gathering and Agriculture. This diagram shows hunting and gathering ecosystems (top) and traditional agriculture systems (bottom) with crops, animals, and higher populations substituted into the ecosystem (Odum 2007, 181).

This intensification led to a more complex civilization with cultural innovation, specialization, and interdependence (Smil 2008). The change in agriculture was reflected by changes in the culture. Early specializations marked the beginning of humans becoming separated from their source of food. As people began to specialize in tool-making or trade, their energy was redirected from the land, yet the land and the energy was still needed to feed those not involved directly in food production. Because of this evolution and the added energy requirements for intensification, other sources of energy were needed. Early sources of extra energy included human slaves and domesticated animals (Pimentel and Pimentel 2008). Cattle, such as oxen and water buffaloes, were used for transporting and plowing as early as 2500 B.C. (Leonard 1973). Animals were also used to power early grinding wheels (Pimentel and Pimentel 2008). This was improved upon later, as humans discovered ways to harness wind and water to power milling; the wind and water were more efficient because they did not require food for maintenance, as did the animals. Old World agricultures also used charcoal (a form of biomass) to create simple farm tools (Smil 2008).

Early civilizations did not depend on vegetation alone for food. The more diverse their food sources, the more stable their food supply. Even early societies recognized the need for diversification. Animals presented an opportunity to store biological energy that was in excess during successful, productive years, and a supply of food in periods of poor conditions (Pimentel and Pimentel 2008). Surplus yields of the good seasons were often fed to domesticated animals, which could be harvested for food when drought, flood, or disease plagued the crop harvest. Livestock, such as chickens, ducks, pigs, rabbits, sheep, goats, cattle, camels, donkeys, and llamas, provided meat, high energy fat, milk, and blood to meet energy, protein, and other nutrient needs. Eventually, the domesticated animals became a continuous source of food

(Pimentel and Pimentel 2008). Those societies inhabiting marginal lands benefited from animal husbandry making them less vulnerable to the unpredictability of crop production. Grasses and forages also grew well in many marginal areas. The forages, unusable by humans, were a food source for livestock, which could harvest this indirect solar energy. The energy was transferred to humans in the form of meat, milk, or blood when eaten (Pimentel and Pimentel 2008).

The second precedent study presented examines the energy inputs and outputs of a slash-and-burn agricultural society in New Guinea's tropical mountainous ecosystem.

Precedent Study: Primitive Agricultural Society in New Guinea

One group that stores excess food energy in pigs and slaughters the pigs during lean years is a primitive agricultural society in New Guinea. The New Guinea villagers practice a "swidden" or "slash-and-burn" type of agriculture (Rappaport 1971), in their tropical, mountainous ecosystem, planting and harvesting plots for about two years, then leaving the land fallow for nearly 20 years before returning. This allows nutrients to build back up in the soil (Pimentel and Pimentel 2008).

When the New Guinea community was studied, the diet of the villagers was 99% plant-based with taro, sweet potatoes, fruits, leaves, yams, and bananas being the primary plants. Animal protein was provided by pigs and hunted species such as marsupials, snakes, lizards, birds, and insect grubs. The human labor was intensive, with 42% of the labor required for weeding and 15% for clearing land. Also, energy was required for transporting the food from the garden to homes (Rappaport 1971).

The New Guinea villagers lived within their energetic means. Raising 1 ha of crops required about 739,160 kcal, and the crop produced approximately 11.4 million kcal/ha amounting to an energy input:output ratio of 15.4:1 (Rappaport 1971). If all of this food went to feed people, 13 persons would have had their food energy requirements met by 1 ha, but the villagers fed 45% of the food to their pigs, as a safety for famine years. This lowered the supported capacity to 5.5 persons per 1 ha (Pimentel and Pimentel 2008).

The New Guinea villagers are an example of a society that had a positive energy return on their investment: they did not expend more energy to produce and transport their food than the amount their food provided them. The villagers understood the implications of the first energy law and used it to their advantage by storing biological energy in pigs. The accumulated energy increased their energy gradient away from equilibrium and provided a safety net for lean years. However, storing energy in animals is not the most efficient use of solar energy, as the second law dictates that losses are incurred with each conversion, though it was necessary for survival of the villagers. This indicates that a balance existed between the needs of the people, the landscape, climate, and available resources.

Animals in Agriculture

Some early societies were pastoralists. Pastoralism is the practice of herding domesticated animals to new pastures thereby encouraging the conversion of phytomass, a form of indirect solar energy, into food. Smil (2008) noted that pastoralism was an adaptation to arid landscapes, often practiced in areas of East Africa, Asia, and the Middle East. Pimentel and Pimentel (2008) pointed out that in wet, dry, cold, or mountainous environments unsuitable for crop production, livestock can convert unusable browse, forbs, and forages to meat, milk, and blood, which humans can utilize. As the New Guinea villagers understood, animals are also a way to store biological energy. Pastoralism could support 0.9-2.8 people/km^2, as shown in

Figure 4.1 (Smil 2008). Population rise in pastoral societies lead to large herds that decreased the ability of those societies to survive due to the land degradation brought about by increasing herd sizes to feed the increasing population. The result was overgrazing. The effects of overgrazing are shorter soil regeneration cycles, increased soil erosion, nutrient decline, and eventually loss of grazing sites (Smil 2008).

In addition to providing a back-up energy source, animals also recycle the nutrients of the plants they consume, and spread them out over the land they graze, without much energy required from humans. Herding consumes little energy, and, in early societies, was often a task delegated to the young or old people who were not able to fulfill hard labor tasks (Pimentel and Pimentel 2008; Smil 2008). The animals worked to gather their food, digest it, and expel the nutrients back into the soil. The co-existence and integration of animals into cropping systems offered stability to food systems in early agricultural societies. In some societies, the animals also offered more than just a food source—they were an important energy source for labor, too.

Where humans can exert a sustained average of 75 W, animate labor provides power ranges from 400 W to 800 W, depending on the animal and the breed (Smil 2008). A typical eight-fold increase in power, animals are able to perform nearly 30 MJ/day of useful work, which is up to 13 times what a human laborer can output (Smil 2008). Plowing, an energy intensive job that once relied heavily on animate power, dates as far back as 4000 B.C. in Mesopotamia and was a critical part of Greek and Roman farming (Smil 2008). Animals were also used to transport commodities for trade and to process the harvest, which could consume large amounts of energy (Smil 2008). Once developed, wind or waterpower was sometimes substituted to help process food, as the machines set up were immobile and more suited to stay in one location compared to the expanses of field that needed to be worked by a mobile source of power that draft animals provided. The incorporation of draft animals into farms marked the change of farmers being the key sources of work in the process to "controllers of larger energy flows," (Smil 2008, 161).

The Needs of Intensification: Irrigation, Nutrients and Crop Diversity

Intensifying agriculture demands water, nutrients, and crop diversity (Smil 2008). Water and nutrients allow for the increase in biomass, while crop diversity helps balance pests, disease and microbial communities in the soil to maintain health and water and nutrient cycling within it. In traditional agriculture all three areas were under constant innovation and though the farming methods were "traditional," the tradition was flexible (Perfecto, Vandermeer, and Wright 2009) and constantly evolving—it had to be to adapt to the vacillating weather, dynamic ecosystems, and changing populations. New technologies and systems were the responses to the effort to make life easier and grow enough food; in traditional agriculture these practices were mostly renewable, with the exception of clearing more land for cultivation.

Irrigation, unless gravity-fed, is an energy intensive practice, yet an important one. Smil calculated that spring wheat yields could be reduced by 23% without irrigation, assuming a 20% water deficit (2008). But, getting water to the crops came at a high energy cost: 100-250 kJ/m^3 of water was required for human-powered low lifts and animals could power medium and high lifts with 4.5-6.5 MJ/m^3 (Smil 2008). Irrigation was imperative in arid or semiarid regions once cultivation occurred on lands that were not saturated by seasonal floods or when rising populations demanded increased cropping. The Sumerians were the first to intensify their farming methods with irrigation, followed by the Egyptians (Smil 2008). Secondly, irrigation was necessary to overcome seasonal rainfall deficits. Rice cultivation in the northern parts of monsoonal Asia (Punjab, North China Plain) required a unique irrigation system for flooding the paddies (Smil 2008). Until fossil fueled pumps ran irrigation systems, a myriad of mechanical devices were invented to help earlier societies get water to their crops. Materials ranged from ropes to wooden poles, bamboo pipes, and clay pots. Humans and animals powered the various technologies, though wind was employed in some areas.

Technologies such as the Archimedean screw required constant cranking of a wooden double helix inside a cylinder to lift water a distance of 25 cm at 30 m^3/h with two men laboring, or 75 cm lifts could be achieved with an input of 15 m^3/h (Smil 2008). To put this in perspective, if only 50% of the water needed were supplied by irrigation for a typical grain crop, 3,000 m^3/ha would be required. The irrigation needed varies among regions and crops in cultivation, but in general, the total seasonal water need was about 1,000 times the mass of the grain harvested (Smil 2008). The amount of nutrients in the soil that the water was taking up into the plant was also an important factor in production.

Nitrogen, phosphorus, and potassium are three critical nutrients for crop growth. Nitrogen is usually the limiting nutrient in most agricultural systems. Replenishment of nitrogen was achieved by three main strategies in traditional agricultures: plowing crop residues into the soil; recycling animal wastes, human wastes, and other organic materials; and planting legumes that could fix nitrogen in the soil. These methods also benefit the soil's moisture holding capacity, infiltration, and aeration (Smil 2008). Recycling nutrients in the form of urine and excrement was a labor-intensive task for traditional agricultural societies that resulted in higher yields. In China, at least 10% of all agricultural labor was devoted to managing fertilizers. Handling and treating the wastes, from hauling to and from confined animal stalls to composting or liquid fermentation and distribution, are all considerations in energy evaluations (Smil 2008).

In Flanders, England in the 1700s, manure, night soil, oil cakes and ash were commonly spread over fields at an average of 10 t/ha, with some rates up to 40 t/ha. Some of the organic wastes were brought back to the farm from cities and towns. Using values from a study conducted in north China in the 1920s, Smil (2008) estimates that human energy expended on fertilizing with organic wastes resulted in more than a 20-fold return on energy in the form of cereal. Nutrient management could also be enhanced through green manuring, as it was in Europe from ancient Greek and Roman times, and also in East Asia from the 1500s. Nitrogen-fixing legumes, especially vetches and clovers, were planted to capture nitrogen from the air and deposit it into the soil (i.e. nitrogen fixation). These legumes could fix 100-300 kg N/ha per year, and many varieties, such as peanuts, were edible. By planting edible legumes, the work was done by the plant, saving humans the labor. All preindustrial intensive agricultural operations that used crop rotations utilized this practice (Smil 2008).

Legumes worked well in combination with other crops, which leads to crop diversity—the third principle path to intensification. Cereals and legumes balance each other in cultivation and in the human diet. Cultures all over the globe benefit from the synergy between the two: China's soybeans, peas and peanuts in combination with millets, rice and wheat; India's lentils and chickpeas alternated with grains, wheat, and rice; Europe's peas and beans with wheat, barley, oats, and rye; West Africa's peanuts and cowpeas mixed with millets. The legumes are higher in protein and the amino acid lysine, which balance the cereals that lack lysine. Other legumes, peanuts and soybeans, can be pressed for oils to add energy to diets. Crop diversity also supports another balance—a vital balance needed to keep pests, pathogens and disease in-check within agricultural systems. In addition, soil tilth is improved while soil erosion is reduced with crop diversity (Smil 2008).

Three societies provide examples of the intensification of traditional agriculture in the pre-fossil fuel era: the Egyptians, Chinese, and Europeans. The following three sections are precedent studies providing energy perspectives of these three societies.

Traditional Agriculture in Egypt

Egyptian agriculture changed little from 3300 B.C. through the next five millennia and began the shift to intensification early because of the limited arable land and the annual floodwaters. The food supply of the Egyptians was supplemented by hunting—animals such as antelopes, crocodiles, pigs and elephants, as well as fowling, fishing, and gathering (Smil 2008). Wheat and barley were the first cereals, and sheep were the first domesticated animals of the Egyptians. Resourcefulness is evident in the Egyptians' harvesting techniques—first, the grain was cut high above the ground for easier transport and cleaner threshing. The remaining straw could be cut for weaving, brickmaking, or as fuel for the kilns (Smil 2008). Oxen energized the plowing, and sheep were utilized for trampling seed into the ground. Other domesticated animals of the Egyptians were cows, donkeys, and goats.

Early farming supported 1-1.3 people/ha at a minimum, densities that significantly increased in the next few thousand years as land was converted to cultivatable area through the removal of trees and grasslands, diking, and drainage. Irrigation efforts revolved around regulating the floodwaters, including building higher levees, impeding drainage channels, and subdividing watersheds (Butzer 1984). Over the 5 millennia of intensification, Butzer (1976) shows the human carrying capacity rising from 1.3 people/ha in 2500 B.C. to 1.8 people/ha in 1250 B.C. to 2.4 people/ha in 150 B.C., at which time the produce supplied 1.5 times the amount of food needed for the 5 million people, reserving 25% of the harvest for seed and accounting for

10% storage losses (Smil 2008). Decline and stagnation ensued for centuries following, until year-round irrigation through control of the floodwaters increased the multicropping numbers after 1800. By the mid-1920s, the farming method was mostly traditional, though inorganic fertilizers had already begun to be used—at this point the land was supporting up to 6 people/ha of farmed land (Waterbury 1979).

The traditional agriculture of the Egyptians shows responses to the principles of energy. The Egyptians employed harvesting techniques that minimized excess weight of the harvested crop for more efficient transporting, and the "waste" or straw was turned into good such as baskets, bricks, or fuel for kilns; this reduced the need for off-farm inputs and avoids energy losses ensured by the second law. The Egyptians also used biological energy for plowing and creating good soil to seed contact in the fields, whereas mechanical energy now powers both of these functions. Also, 1.5 times the amount of food required by the population was produced in Egypt, but 25% went to seed for the following year and storage losses accounted for the other 10%. This way the Egyptians avoided importing seed to the farm and the energy costs associated with seed inputs. That they grew enough to compensate for losses exhibits a regard for nature; the Egyptians, though perhaps because there was no other option, accounted for the amount of the harvest that would be lost to pests and disease. Today, energy expensive pesticides and herbicides are used to maximize the amount of harvest from each acre, without regard for the natural processes in nature—instead the single-purpose goal is to use pesticides to kill any organism that tries to have a share in the harvest. This creates a hole in the food web, and eventually imbalance in the system. By accounting for the 10% lost, the Egyptians enabled all scales to be energized and to fulfill their functions in the ecosystem. Finally, as the Egyptians intensified agriculture, they had years of growth with increases in production later to be followed by a period of decline until after 1800 (Smil 2008). This phenomenon is in line with the fifth energy law concerning energy hierarchy. The production pulses were a result of an accumulated storage with frenzied releases.

Traditional Agriculture in China

The traditional agriculture practiced in China was assisted in the innovative tools developed: the square-pallet chain pump, extensive regional irrigation systems, horse collar harness, iron moldboard plow, multi-tube seed drill, and a variety of horse-drawn hoes and ridgers (Smil 2008). The traditional Chinese way of farming includes intensive multi-cropping, recycling of organic wastes, and widespread irrigation. Dryland millet and rice were the main staples grown in the first millennia, and pigs were the first domesticated animals. The Chinese system was labor-intensive, complex, and vulnerable, yet self-sustaining.

The typical farm had fields of an average 0.4 ha, and these fields were normally about 600 m (656 yards) from the farmhouse (Buck 1937). Farm size ranged from less than 5-13 acres, with 5 acre farms being considered “medium-sized” and 13 acre farms being “very large” (Buck 1949). Buck (1949) also reported that “economic-sized” farms vary from 6.2-20 acres across different agricultural regions in China, depending on soils, climate and type of farming. The average “economic-sized” farm was 8 acres (Buck 1949). Usually, around half of the fields were irrigated, 25% terraced, and 95% cropped with buildings, ponds, roads, and graves covering the rest. Of the cropped land, 90% was planted in grains, 4% in sweet potatoes, 2% in fibers, and 1% in vegetables (Smil 2008). Most farm implements were hand tools or animal drawn tools and carts, which were well designed and of quality workmanship. Economically, 80% of the farms are too small and were not financially sound, “even under Chinese conditions” (Buck 1949, 365). The population density of Buck’s (1949) study area was 0.5 ac/person.

The traditional Chinese diet was integrated with the land and balanced to fulfill the nutritional needs of the people. Organic waste recycling was vital in these systems, and everyone was needed to work—human labor was the source of fieldwork, and plowing and harrowing was done with the help of oxen and water buffalo. This required 275 10-hour days of labor (in adult work units) for the average family of six. Draft animals subsisted on grasses, unusable as human food, allowing the energy returns to be calculated by using human labor budgets, according to Smil (2008). The harvested energy to labor energy ratios were approximately 25 for grains and sweet potatoes, 40 for corn, 15 for pulse crops (i.e. edible legumes) and 10 for plant oils; grains provided 90% of the human food energy. High population densities were possible by eating mostly crops and only eating animal products for special occasions (Smil 2008); the added transformation of energy through the animal makes animal products energetically expensive. This tradeoff resulted in a lack of stored biological energy during famine years, to which China was vulnerable. During the 1920s, peasants recalled famines that forced an estimated 25% of the population to eat bark and grasses and 15% to leave their communities in search of food.

The traditional agricultural system in China also offers some insight to operating without fossil fuels. Biological human energy was used for fieldwork and animate labor for plowing and harrowing. Also, the Chinese recycled organic wastes to boost yields, instead of importing synthetic fertilizers. Though the organic nutrients often came from offsite, they were likely the recycled nutrients of food previously produced on the farm. Just as importantly, they nutrients were produced nearby through biological processes, minimizing losses in production and transporting.

The Chinese precedent study offers important information regarding the scale of farm fields. The fields were only about 0.4 ha (1 acre) in size, and on average the fields were just 600 m (656 yards, 0.37 miles) away from a farmhouse (Buck 1937). The size of the fields and distances are not just happenstance; the size and distance of fields to farmhouse imply that the Chinese sited these places to minimize energy expended in walking and hauling in order to maximize energy efficiency. Without any type of mechanized vehicle, the Chinese designed for the most energy possible to go into productive work and the least possible amount of energy expended on moving and hauling. That the farmhouse is 600 m of the fields is no coincidence either. The farmhouse served as a spatial center where the laborers most likely left from in the morning, carrying seed or other tools, and returned to, with the harvest or tools. The tools and labor to preserve the harvest was located within close proximity to the farmhouse. The farmhouse correlates to the camp of the earlier hunting and gathering societies. The same energy principles apply—the energy cost increases as the distance from the farmhouse or camp increases, and at some point the energy cost curve rises sharply. The heavy reliance on crop production resulted in very little emphasis on stored biological energy in animals. The lack of stored energy resulted in famines and very stressed conditions during famine years. However, by eating closer to the sun, the Chinese reduced transformations and supplied more edible energy to a higher population density.

The scale of farms is also important to note. Individual farms across various regions of China occupied 5-20 acres, and the average "economic-sized" farm was 8 acres. The variables influencing farm acreage, as noted by Buck (1949), were soils, climate, and type of farming—in other words, the farm size was a response to the physical environment in which it was located. Just as importantly, the agricultural program and farm size were influenced by the cultural environment. The population pressure was of significance to the production type, farm size, and even feasibility of mechanization. According to Buck (1949), "Those who believe that mechanization is a solution for agricultural problems in China usually know little about farm management… but, general mechanization is impracticable until favorable [decreased] changes occur in the man-land ratio, until machinery is available at low prices, and until there is a cheap source of power" (366). Buck also points out that a farmer with machinery would finish his work earlier and have nothing else to do, but would take on greater expenses and go bankrupt quickly. Essentially, Buck is saying that the use of subsidized energy is impractical when the cost of machinery and power (i.e. fossil fuel) is above some threshold and when there are enough people to work the land. "Until machinery is available at low prices, and until there is a cheap source of power"—this point is arguable. Energetically, it is now understood that the excess energy entering into a system promotes feedback subsidies, which foster a false carrying capacity, at least while there is "cheap power" (Odum 2007). However, globally, we now have this false carrying capacity and must find ways of doing without cheap power.

Traditional Agriculture in Europe

The traditional agricultures of Europe heavily practiced animal husbandry in addition to rotating cereals and legumes. During the age of the Roman Empire, green manures were often plowed-in, organic wastes were recycled intensively, and lime was spread over the fields to improve pH. For plowing, oxen were employed, seeds were sown by hand, sickles were used for harvesting, and flails were used in threshing, and milling was done by hand. After the fall of the

Western Roman Empire, the scythe replaced the sickle, horses replaced oxen as draft animals in many regions, fallowing was common, the intensity of spreading manure varied, and legumes were grown in diverse rotations. Throughout, harvests were highly variable.

Prosperous years, 1150-1300 and 1450-1550, coincided with extensive conversion of land—from wetlands and forests to fields. Famines, abandoned villages, and soil erosion marked years of decline. The 1700s brought about more intensification through better implements, cessation of fallowing, regular manuring, and adoption of standard rotations, in particular Norfolk's four-year succession of wheat, turnips, barley, and clover, which tripled the rate of symbiotic nitrogen fixation (Campbell and Overton 1993). Norfolk's four-course rotation, as it was also called, required a root crop to be grown in the first year, followed by oats or barley in the second, and a legume (usually clover) in the third, ended by wheat in the fourth. Sheep were an integral part of the system, consuming the cover crop and recycling the nutrients. This form of nitrogen in organic matter (OM) led to higher yields and ultimately a population growth that helped spur industrialization. Wheat yields soared between 1820 and 1860 due to land drainage, crop rotations, and manuring. At this time, British agriculture was still solar powered, but coal-based manufacturing in the form of better tools had already begun benefitting farmers by providing better tools. The population density of arable land went from 2-2.5 people/ha during the Middle Ages to 4-5 people/ha by 1800. By 1900, 8-10 people/ha were supported by the land in the most intensely cultivated regions—by this time, large inputs of fossil energy were gradually becoming the norm across Europe (Smil 2008).

Energetically, Europe also stored biological energy in animals and used animate labor in farming. By using legumes, they reduced the need for nitrogen fertilizer inputs into the farm system, and the legumes also provided soil coverage and organic matter to feed the microorganisms in the soil, maximizing power across the scales in the system. Energy costs were reduced also by using organic wastes instead of synthetic fertilizers—the organic wastes also provided organic matter in the soil.

Europe also experienced the intrinsic pulsing pattern of energy hierarchy. In Europe, growth was due to the expansion of agricultural land as forests and wetlands were converted. Growth of this sort must end as land runs out. Also, energy flow across scales is not honored as ecosystems are destroyed, and we now know that conversion of land, especially deforestation, impacts our global carbon cycle (Smil 2008). As characteristic of pulsing, the frenzied releases were followed by periods of accumulation, marked by famines, abandoned villages and soil erosion in preindustrial Europe.

Lessons Learned

Early agricultural societies functioned within their energetic means. The EROI of these societies was greater than or equal to one, as demonstrated in Table 4.3, as they operated without a subsidized energy source. Security and vulnerability was addressed through stores of energy in biological forms such as pigs, sheep, cows, and other species of animals. These stores of energy were not so great as to permit an unchecked population growth, and any population growth required more energy to produce food. This energy was provided by humans and was biological instead of mechanical. Humans would tend the fields, reap the harvest, and recycle the nutrients back into the system. A model of this mostly renewable agrarian landscape is shown in Figure 4.4.

Table 4.3. Energy Return on Energy Invested and Supported Population Density from Various Modes of Food Production. The values for EROI range widely depending on environment (soil, climate, etc.) and methodology for calculating EROI. The supported density varies too due to differing conditions in various locations. Notice that only modern agriculture has an EROI less than 1.

Energy Return and Supported Population Density of Various Modes of Food Provision		
Mode of Food Production	EROI	Supported Density (ppl/sq km)
Hunting-Gathering/Foraging	3.3[b]-10[a]	0.01-1[d]
Pastoralism (Traditional)	N/A[d]	1-2.5[d]
Swidden/Slash-and-Burn/Shifting Agriculture	11-70[d]; 40[a]	10-60[d]
Traditional Agriculture	1-5[a]	100-900[d]
Modern Agriculture (in the U.S.)	5.04[b]-0.025[c]	900-2,000[d]

N/A – Varies significantly depending on conditions/environment
[a] Lough 1999
[b] Pimentel et al. 2002
[c] Schramski et al. 2013
[d] Smil 2008

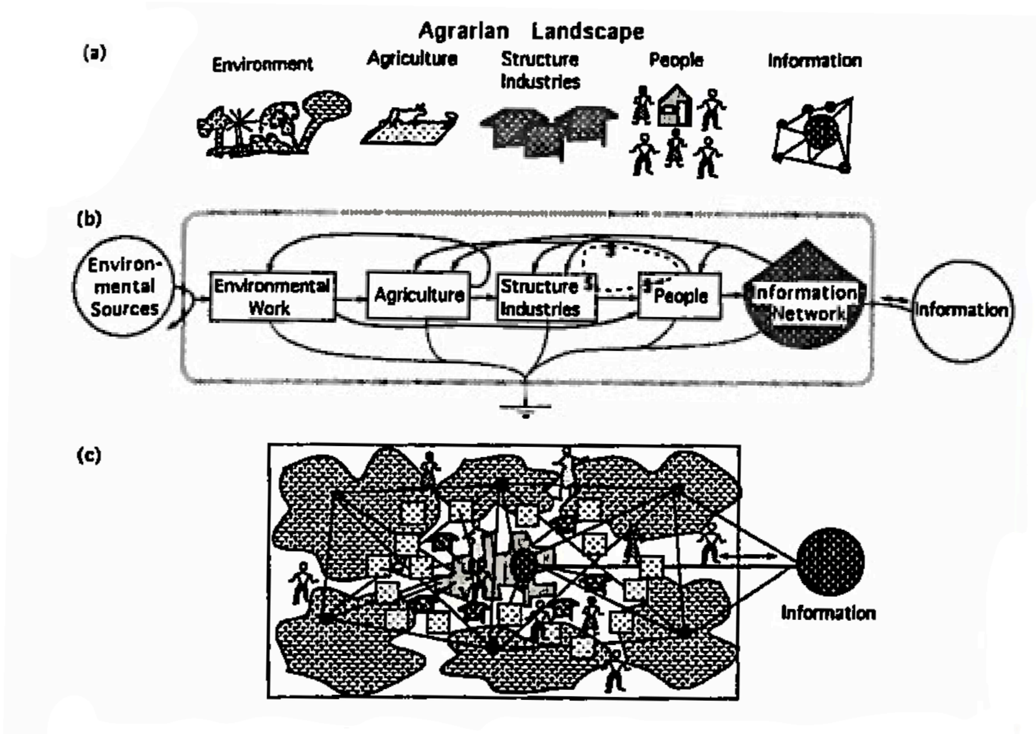

Figure 4.4. Diagrams of Mostly Renewable Traditional Agrarian Landscapes. (a) Five zones from rural to spatial centers; (b) Energy systems diagram of the agrarian landscape; (c) A plan view (Odum and Odum 2000, 114).

Introducing draft animals into agricultural operations required energy in the form of phytomass from the system, but also supplied energy into the system. The second law requires a conversion loss from solar to phytomass to animate labor, but the amount of work the horses provided compared to the land required to sustain them versus the same amount of land to grow food for more humans worked positively energetically in favor of draft animals (Smil 2008).

These traditional agricultural societies remained mostly intact until the Industrial Revolution. Energetically, agriculture became subsidized when trees began being cut for charcoal to make tools and implements for the animate labor to pull. At that point, stores of solar energy approximately 30-200 years old were transformed to heat energy to smelt ores into tools.

Eventually, older stores of energy, which were higher in energy density, began to be used to make tools. The fundamental flaw was these societies had begun reaching beyond their boundaries. An industrial society was on the horizon. In the post-industrial era, all the boundaries will have been pushed, and no more land or old stores of energy will exist. A world without fossil energy will require that societies live within their energetic means again. Therefore, the focus of this research is on the agricultural practices of societies with a positive energy return.

Fossil-Fueled Agriculture

Agriculture: From the Dawn of the Fossil Fuel Era to Pre-WWII (1940)

With fossil energy on the horizon, two very different forms of energy began competing: biological and machine (Berry 1977). Draft animals were still the norm as coal began being mined in England in the 1500s. Coal-fired power did not take off until 1769, the year James Watt invented the steam engine, leaving agriculture to continue operating on solar power with the help of some new implements compliments of fossil energy manufacturing. Many of these implements were attached to draft animals for working in the fields. Compared to the amount of food they required, draft animals contributed positively from an energetic balance perspective; Smil estimates that 20-25% of the U.S. farmland was needed in 1918 to feed the working animals that existed during that time—26.7 million horses. Already on the scene in 1918 were 85,000 tractors and 89,000 trucks. Tractors had emerged in only 8 years, from 1910 when only about 1,000 small tractors were on US farms (Smil 2008). But, the tractor would not have been possible without the changes that occurred in England and the Americas in the previous 300-400 years.

In 1492, as Columbus arrived in the Americas, England had already begun a transition in its economy—from a localized trade of food and goods to an economy of manufacturing and money over longer distances. The discovery of new land and new resources, including people, allowed the changes in Europe to flourish. The changes in the use of land and resources were evident in The Enclosure Acts, which essentially forced peasants off of the land they farmed to feed themselves and into the cities, where they had no option but to take low-wage manufacturing jobs (Perfecto, Vandermeer, and Wright 2009). Wendell Berry (1977) writes of the same scenario that was sparked by machinery in America years later that sent millions of farm workers to cities to take menial factory jobs, where complex responsibility was substituted by simple dutifulness, resulting in a simplification of the mind, which, according to Berry, is difficult to reverse. The peasants, and their knowledge and skills, were victim to the new economy and the new need that required the land they had depended on for subsistence. The land was now needed for sheep farming for wool to be used in manufacturing. Because the land in England was becoming increasingly devoted to manufacturing purposes, the colonized land in the Americas was needed to provide food, goods, and luxuries to Europe. The demand for food was rising, but less labor was available to produce it (Perfecto, Vandermeer, and Wright 2009).

As trade grew, cities grew too. The landscape reflected the new needs as mines and quarries were dug into the earth to extract materials for the new urban buildings, ships, wagons, and boxes. Amidst new scientific discoveries and without human energy present to farm the declining agricultural land devoted to crops, the need for food spurred "Scientific Agriculture." Inventors, scientists, entrepreneurs, and farmers began searching for solutions that addressed irrigation, soil fertility, tools, and animal and crop varieties that could produce higher yields. Also of interest was the improvement of transportation to get the food and goods to cities.

Complexity of society was increasing, but simplification was occurring in the minds of peasants and in agriculture itself. The Portuguese had already discovered the profitable investments in islands off the west coast of Africa. There they used forced labor to cultivate monocultures of sugarcane, which brought high prices in Europe. This profitable model was expanded to islands in the Caribbean, and parts of Central, North, and South America. Monocultures replaced previously diverse landscapes, and the plantation model morphed agriculture into an economic enterprise with massed labor and large expanses of land focused on producing one crop. Even in England, diverse, small-scale farms transitioned into big estates that produced one or two main crops because of the profit opportunity to the landholder. James Watts' steam engine and the invention of the railroad provided more support for this system. Cheap and abundant fossil fuels fueled it.

With animals segregated from crop production and the population boom in the cities, the nutrient cycles of traditional agricultural systems that had been in place for millennia were disrupted. As early as the mid-1700s, Europe faced problems from decreased soil fertility. The breakdown of the traditional farming systems that had once integrated all the elements of the landscape (cropland, pasture, forests, streams and rivers, and the even the sea) caused the decline in soil fertility as agricultural landscapes became specialized in one main crop based on the profit it brought when sold to urban populations. More energy was needed to collect, haul, and spread animal wastes and composts that were now segregated from the farm. Fallowing was abandoned to increase profitability, and the traditional knowledge of the integrated farm was becoming rare (Perfecto, Vandermeer, and Wright 2009). A new flow of nutrients replaced the old flow, and fossil fuels would be essential in energetically financing the new flow.

In 1840, Justus von Liebig introduced Liebig's Law of the Minimum, stating that plants needed nutrients in specific proportions and the single nutrient in short supply, the limiting nutrient, would prevent plant growth. This was to be remedied with manufactured nutrients that would be produced, transported, and then spread over the fields. The functions of animals and plant management were replaced with fossil energy inputs. This resulted in the birth of a fertilizer industry. A chemical procedure led to the production of superphosphate, with phosphate rock, guano, sodium nitrate, and potassium being imported from natural sources for manufacturing. Later, ammonia would be synthesized through the Haber-Bosch process. The fertilizer industry supplied the needed nutrients to European land, and by the late 1800s, soil fertility was becoming a problem for farmers in other areas of European settlement. Mineral, and eventually synthetic fertilizers provided a cheap solution. Progress was happening, economies were growing, and so were populations (Perfecto, Vandermeer, and Wright 2009). As long as fossil fuels are cheaper than the profit they can make, they will support economic growth.

Liebig understood the new flow of nutrients and wrote of his concerns. He noted the irrationally of transporting the nutrients to the cities in the form of food and dumping the nutrients into rivers in the form of human waste. What was once a valuable farming input had developed into an agent of pollution and public health issue in cities, while a never-ending shortage of nutrients plagued farms (Perfecto, Vandermeer, and Wright 2009). Yet, by the 1900s, the fertilizer industry had already become the British chemical industry's largest customer. Then came the world wars. The demand for nitrate explosives sparked even more growth in the fertilizer industry (Perfecto, Vandermeer, and Wright 2009). Through fossil energy, humans gained more control over the land than ever before.

Modern Agriculture: From the World Wars to Present

The tractor, built of mined and processed ores, revolutionized agriculture. Able to output the work of many horses, the first tractors were used for plowing and spreading fertilizers. With the advent of the tractor, the need for human laborers declined. Machines began to replace jobs in America and the number of rural inhabitants decreased. One-third of the U.S. population was farm workers in 1910, declining to one-twentieth by 1969, filling the cities with unemployed people. Energy became to be substituted for knowledge and skill (Berry 1977). Tractors grew bigger and are still growing today, proving again Jevons' Paradox: for every improvement in energy efficiency, energy use is increased rather than decreased. The tractor, with all the ease it brings, also has downfalls. It runs off of fossil fuels, and it gives mankind the ability to destruct at a large scale—we can plow and lose our topsoil, we can spread chemicals and contaminate our water supply, and we can compact the soil and create hardpan which contributes to decreased water retention, just to name a few of the negative qualities. Draft animals enforced restraint, as humans had to be able to handle them, requiring responsibility and skill. The tractor will start for anyone with a key and gas money—anyone with or without knowledge of the complexities and sensitivities of the land and our ecosystems. Even to build a tractor requires destructing the earth to uncover ores that can then be refined into metal. "From the beginning, these machines have created effects that society could absorb only at the cost of suffering and disorder," (Berry 1977, 94).

Tractors, ever increasing in size, made farming large acreages of land easier. Bigger implements were also designed to cover larger areas. This mechanized production method is amenable with large monocultures. Large monocultures are more susceptible to pest infestations. Diverse farming operations and crop rotations once maintained balance between trophic levels, but huge stands of one crop in sequential years attracts predators and parasites of that particular crop (pests), but not the predators and parasites of the pests. Because the system is never alternated, the pests settle in, with a constant supply of their favorite food. The balance is lost, and fossil energy replaces it by energizing the manufacturing and transportation of pesticides (Perfecto, Vandermeer, and Wright 2009).

Biocides became widely used after World War II. Before, pests had been managed through a variety of methods including strategic crop rotations, growing resistant varieties, and introducing predators and other natural enemies of pests. World War II raised interest in pesticides as possible biological warfare instruments, leading to government funding of poisons, of which 2,4-D was developed. 2,4-D saw action in Vietnam as an ingredient in Agent Orange and is now a popular herbicide used to eradicate weeds. DDT (dichloro-diphenyl-trichloroethane), discovered in the late 1800s, was found to have insecticidal properties in 1939, and was used to fight deadly tropical diseases spread mainly by arthropods. During World War II, Germany also further developed their arsenal with chemicals. Advances were also made in the efficiency of producing nitrate explosives due to funding for research (Perfecto, Vandermeer, and Wright 2009). Perfecto, Vandermeer, and Wright (2009) claim, “World War II was the seed that germinated the agrochemical revolution” (46).

With the end of the war, business was bound to slow down for the chemical industry, except that the industry, using wartime rhetoric, seized the opportunity to transition into agriculture, capitalizing on emotions and attitudes of the time. Where chemicals were no longer needed to defeat the enemy of war, they were needed “to defeat the new enemy in agriculture,” (Perfecto, Vandermeer, and Wright 2009, 46). Pesticides promised more control and higher yields. However, in addition to killing pests, they also kill or affect the behavior of the beneficial natural enemies of the pests. This may result in pest outbreaks and additional pesticides. Since the middle of the twentieth century, researchers and some farmers have realized that nature cannot be suppressed—faster than the chemicals (i.e. fungicides, herbicides, pesticides) can be developed genes are mutating and developing resistance to the chemicals (Pimentel and Pimentel 2008). For example, a study from the University of Georgia Tifton campus reports glyphosate-resistant Palmer amaranth (weed) in all cotton producing counties in Georgia. The resistance of the weed has more than doubled the herbicide costs following glyphosate resistance and increased the amount of tilling, yet the control of the weed is still inadequate, according to the study. Additionally, the resistance has also led to hand weeding, costing the farmers $57 per hand-weeded ha—a 475% cost increase from the years before the weed resistance. The new management strategies are more diverse, complex and expensive than those used a decade ago, reported the study (Sosnoskie and Culpepper 2014). In the fields and research labs, more energy is being used to combat the resistance that nature is developing.

As evidenced above, the post-World War II agricultural system totally relies on manufactured inputs, resulting in negative energy returns as shown in Table 4.4. Where farms once generated their own inputs, the new inputs must be purchased. Animal power has been replaced by traction power, manure and compost by synthetic fertilizers, and cultural and biological pest management practices with pesticides. Ultimately, humans have been replaced by machines powered by Exxon/Mobile, BP and Shell. These new substitutes are only possible through the harvesting of fossil fuels from the earth, hence bringing us closer to equilibrium with outer space, and leaving us with a smaller and smaller energy gradient from which to harvest in the future, as the human population soars.

Table 4.4. EROIs of Modern Agriculture and Food Wasted in Developed Countries.

EROIs of Modern Agriculture and Percentage of Food Wasted		
Production Type	EROI[a]	% Wasted[b]
Feedlot Beef	0.06	No Data
Vegetables	0.22	(Fruits and Vegetables) 64%
Fruits	0.16	
Dairy products and meat	0.14	(Dairy) 21%, (Meat) 25%
Feed and Grain	0.1	(Grain) 43%

[a] Lough 1999
[b] Gunders 2012 (in USA, Canada, Australia and New Zealand)

As agriculture became simplified ecologically, it became more complicated socially and economically. Originally farming was the process of turning seeds into crops using resources such as energy (labor), land and water as shown in the energy diagram in Figure 4.5 (a). Gradually the shift was made to industrial agriculture, which encompasses the production of agricultural inputs, farming, processing, packaging, transporting and output marketing (Perfecto, Vandermeer, and Wright 2009). In industrial agriculture, farms are larger and more efficient at production with the help of manufactured inputs made possible by fossil energy. Figure 4.5 also shows the energy flows of industrial agriculture. These changes have had social and economical consequences, and as fossil energy supplies decline, we must find creative ways to transition into a lower-energy society with the added responsibility of providing food for many million more people.

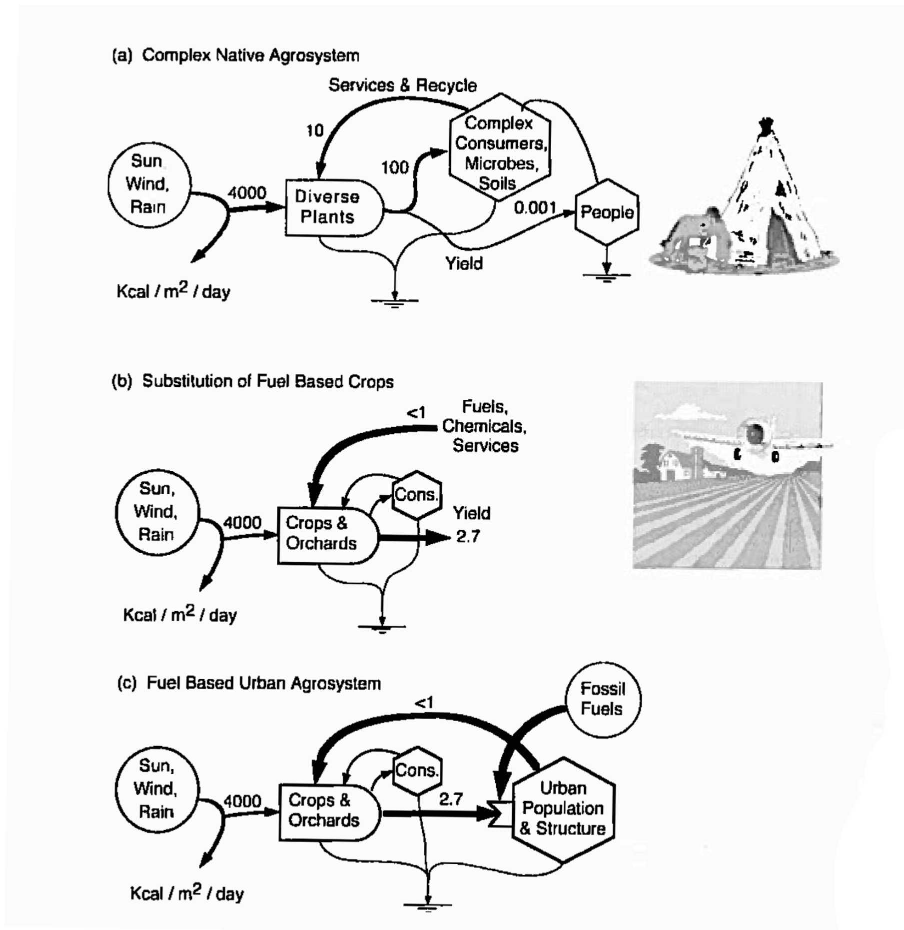

Figure 4.5. Comparing Complex Hunting and Gathering-Gardening Systems with Industrial Agriculture Systems. (a) Self-sufficient low input, low yielding system; (b) high yielding system with fossil energy substituted for natural functions; (c) Industrial agriculture aided by urban society—mechanized planting and imported seeds replace natural dispersion, fertilizers replacing nutrient management, chemical weed management replacing woody maintenance of a shading system, soil management replacing the forest soil-building process, insecticides replacing natural diversity and new manufactured varieties replacing local genetic selection (Odum 2007, 188).

Consequences of Complexification

Using animals, and later machinery, required more technical skill on behalf of the farmer. It also called for more skill in terms of responsibility to other life, the understanding of value, and skill as the connection between life and tools, or life and machines. Once measured qualitatively (e.g. how *well* a person works), skill is now often measured more quantitatively (e.g. how *much* a person can produce), and as skills become more quantifiable, the easier they are to replace with machines (Berry 1977). According to Berry (1977), replacing skills with machines separates us from life, and sparks the removal "of value—of essential sources, dependencies, and relationships," (92). The replacement of people on farms with machines and the ensuing disconnection to the land is shown in Figure 4.6, a model of urban America. When machines are allowed to replace humans and human skills, we lose those skills, degrading ourselves, and we diminish life, yet it is called "prospering" (Berry 1977, 92).

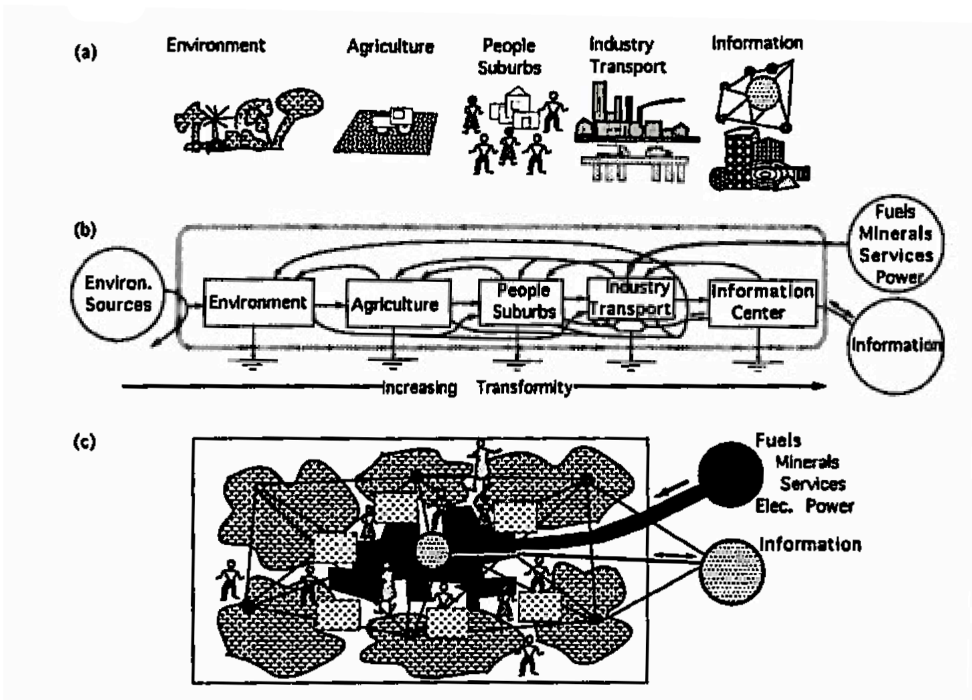

Figure 4.6. Model of the Industrial Landscape of Urban America. (a) the fives zones from the rural environment to the city; (b) energy systems diagram; (c) plan view (Odum and Odum 2000, 116).

As technical skills are gained, new skills are imperative to avoid destruction. Berry (1977) uses the example of the digging stick—once a skill was gained that could disturb the earth, other "skills of responsibility" were needed that would preserve the earth and restore its fertility (92). With the advent of farm machinery powered by fossil fuels, skills of manual labor and responsibility went into extreme decline. The switch from animate labor to machine power freed people of "any restraint or moral limit on behavior," as machinery is directly responsive to human will, unlike animals (Berry 1977, 93). Machines are justifiably substituted for humans and animals due to their speed and production volume. Yet, the tradeoff for speed is quality, which has cultural importance, but not an immediate economic payoff as quantity does.

Machines bypass restraint—the first principle in any biological system, according to Berry—and the "natural or moral checks that maintain a balance between use and continuity." Berry continues, "The life of one year must not be allowed to diminish the life of the next; nothing must live at the expense of the source," (93). In nature the checks and balances come from food species in combination with predators and pests and disease. In agriculture, as humans have removed the checks and balances, responsibility should ensue concerning soil erosion, biodiversity, crop rotations, nutrient cycling and other protections of the source. The problem lies in the economic return required of the machines, and the demand of production, which requires speed—and inherently, a decline in quality. "As the skills of production decline, the skills of responsibility perish" (Berry 1977, 93-94). This complex explanation relates the technological advances with cultural factors, and ultimately the ecological degradation that threatens mankind's ability to survive.

Acknowledging the realities of fossil-fuel use and machine power impact on the land and air requires that we must alter our practices. The way forward is debated, and landscape design alone cannot solve the problems, though the design of the landscape may provide the infrastructure to foster a safe solution. In regards to scale, the agricultural landscape can constrain the type of management alternatives, and even machines of consideration. Berry (1977) writes,

> "To argue for a balance between people and their tools, between life and machinery, between biological and machine-produced energy, is to argue for restraint upon the use of these machines. The arguments that rise out of the machine-metaphor—arguments for cheapness, efficiency, labor-saving, economic growth, etc.—all point to infinite industrial growth and infinite energy consumption. The moral argument points to

restraint… we will have either to live within our limits, within the human definition, or not live at all," (94).

Landscape foundations can lead the way in providing a vision for functional and energy independent agricultural systems. Coupled with policy, marketing, and education, energy-based landscape design has the opportunity to address social as well as ecological issues. By addressing energy, our society can find creative ways to meet our *needs* and move forward into the next era of food production sustainably.

Landscape architects, with integrated training in the arts and sciences, are well suited to take on such a challenge as designing to reduce energy inputs in farming systems to contribute to this step forward. In fact, early American landscape architects, referred to as "landscape gardeners" in the 1800s, were horticulturalists who were interested in the technical details of soil health, plant propagation and pomology, as well as aesthetics and the ideas of the American landscape (Tufts 2008). Andrew Jackson Downing, one such early practitioner, discussed soil improvement, fruit orchards, farming technology, and garden and homestead design in his book, *Rural Essays* (Downing 1853). Liberty Hyde Bailey was a proponent of "educated" gardening and farm production, and his work contributed to the formation of the Cooperative Extension Service (Tufts 2008). Later, as America became more industrialized in the twentieth century, the rural focus gave way to urban and public space design. In 1969, landscape architect Ian McHarg authored *Design with Nature*, advocating for an ecological approach to design, even when planning urban centers. Though he was not an agriculturalist, he was an important proponent for designing *with* natural systems. We see that throughout the history of landscape architecture, practitioners approached design, even the design of agricultural land, with an understanding of the natural laws and physical sciences. As discussed in the next chapter, it is not only vital to begin designing with the laws of energy in mind—it is the duty of a landscape architect. The next chapter introduces the energy-based design guidelines for designing lower input agricultural systems.

Chapter Four Analysis

This chapter reviews the role of energy in the history of agriculture. The precedent studies presented introduce evidence of responses to the energy laws. Below is a matrix representing the energy principal evidenced in the precedent studies of preindustrial agriculture. Though not all of the boxes indicate a response to the laws of energy, it is certain that each principal impacted each society to some extent. However, when creating this matrix, the author used only information from the research and noted the strong responses.

To determine the information in the matrix, each precedent study was analyzed to see if any evidence existed indicating that any behaviors of the particular society were an acknowledgement to each energy principle. The question was asked: Did this precedent study show a response to this energy principle? If the answer was yes, the box was checked. See Table 4.5 below for the results.

Table 4.5. Energetic Responses of Preindustrial Societies (Graphic by author, 2014).

Evidence of the Energy Laws in Precedent Studies									
	1st Energy Law	2nd Energy Law	Spatial Hierarchy	Concentration	Information	Time and Storage	Scale	Energy X Scales	Natural Energies
Hunters-Gatherers: !Kung Bushmen	■	■	■	■	■	■	■		■
Shifting: New Guinea Villagers	■	■	■	■	■	■	■	■	
Traditional Agriculture: Egypt	■	■		■	■			■	■
Traditional Agriculture: China	■	■	■	■	■	■	■		
Traditional Agriculture: Europe	■				■	■		■	

These societies that existed without fossil fuels offer insights on how to design agricultural systems to reduce energy inputs. How these societies coped with the restraints of low inputs provides proven references for the design of low input systems. These precedent studies will appear as historical references in the next chapter.

CHAPTER 5

ENERGY-BASED DESIGN

Landscape architects are trained to design the flow of resources. Often these “resources” include humans, vehicular traffic, stormwater, and nutrients. A common goal is to design for efficiency, balanced with many other goals such as supporting biodiversity, aesthetics, and acknowledging financial cost, etc. Energy, an intangible flow, is more difficult to understand and design for. Yet it is crucial that we, as a society, begin thinking more in terms of the expenditure and conservation of energy, because without a subsidized source such as fossil fuels, life will radically change. Our dependency runs deep—even the renewable energy technologies are based on using fossil fuels for mining, transporting, manufacturing, distribution and construction. As discussed in previous chapters, we are running out of affordable, abundant energy, and our landscapes are already changing dramatically due to this fact.

Just as we must design with regard to natural laws, we must also consider the human “laws” of ethics. The American Society of Landscape Architects Code of Professional Ethics (ASLA) states that the profession of landscape architecture is dedicated to the public health, safety, welfare and recognition and protection of the land and its resources (ASLA Code of Professional Ethics 2013). The extraction and burning of fossil fuels is harmful to the ecosphere and therefore the public health, safety, and welfare as we are a part of the ecosphere. Mining and extraction of the high-energy carbon stores is in no way protecting the land or its resources either. Wendell Berry (1977) addresses the interconnectedness of our bodies, our health and the health of the ecosphere. He writes,

> "… the concept of health is rooted in the concept of wholeness… Our bodies are also not distinct from the bodies of other people, on which they depend in a complexity of ways from biological to spiritual. They are not distinct from the bodies of plants and animals, with which we are involved in the cycles of feeding and in the intricate companionships of ecological systems and of the spirit. They are not distinct from the earth, the sun and moon, and the other heavenly bodies… It is wrong to think that bodily health is compatible with spiritual confusion or cultural disorder, or with polluted air and water or impoverished soil" (103).

Yet, every step in the process of obtaining and using fossil energy damages the earth and all its inhabitants. If the standards declared by the ASLA are the standards by which landscape architects are to design, it is imperative that landscape architects design with regard to fossil energy usage when constructing their designs, as well as the energy required for management and maintenance. In a world without cheap fossil energy, the design of our food producing landscapes will be the most critical.

The layout of agricultural systems influences the energy needed for current and future management, or operational energy. The design guidelines set forth below are intended to reduce energy needs in rural agricultural systems, providing considerations for new farms or existing farms, and lay the foundation for an operation to be managed with minimal direct or indirect fossil energy inputs. Ultimately, these guidelines strive to provide a more reliable, stable, energy-independent food sources for the future. The design guidelines are not expected to eliminate fossil energy inputs and usage alone, just as they are not expected to reduce the need immediately. The goal is to provide ways to reduce energy needs and therefore energy costs, and to initiate a transition into independence from fossil energy to buffer the effects of rising fossil energy prices and eventually support a world without fossil energy.

The rest of this chapter contains the methodology, the design guidelines, an analysis of their possible impacts and the conclusion. The design guidelines are organized by the energy law or principle from which the guideline originates.

Methodology

In Chapter Two, a list of the energy principles was developed. These energy principles form the basis of the design guidelines. The energy principles are directly from the classic laws of thermodynamics and the more recently proposed law of energy hierarchy (i.e. the Fifth Law of Thermodynamics). Odum proposed the law of energy hierarchy and explained how energy hierarchy is accounted for in nature—through spatial orientation, concentrating materials, information, time and storage, as a measure of scale, across scales, and in the landscape. The classic laws account for single processes, whereas energy hierarchy explains the behavior of energy across scales. Therefore, the classic laws help define the farm system and account for the energy flowing in and out. Energy hierarchy, as it explains the flows through the landscape, provides a basis for designing the actual farm landscape to promote low energy flows.

Chapter Three reviewed energy analyses of agricultural systems. From these studies, a list of all the inputs was generated, then similar items were grouped together and classified into 12 categories, as shown in Table 3.5 and Table 3.6. In Chapter Four, we reviewed the history of agriculture and reviewed precedent studies. In Table 4.5, societies from the precedent studies were analyzed regarding their strategies for survival on low energy budgets. These precedent studies helped to understand the flow of energy in low input systems, and the physical limitations encountered by the preindustrial societies, which reinforced the design guidelines by providing a historical reference.

The matrix below, Table 5.1, explains the development of the design guidelines. For each box, the potential of each energy principle to impact that particular input was analyzed, given the understood flows of energy in agroecosystems. If the principle could directly or indirectly affect the input, it was considered how the farm landscape could be designed to respond to the particular energy principle. This is the process followed to establish the guidelines.

Table 5.1. Energy Principles Analyzed against Energy Inputs (Graphic created by author, 2014).

Energy Principles and Energy Inputs									
	Classic Laws		Fifth Energy Law - Energy Hierarchy						
	First Law	Second Law	Spatial Hierarchy	Concentrating Materials	(Biological) Information	Time + Storage	Measure of Scale	Across Scales	Energy Convergence
Labor	■	■	■	■	■		■		■
Machinery	■	■	■	■			■	■	■
Fuels	■	■	■	■			■	■	■
Fertilizers	■	■		■	■	■		■	
Amendments	■	■		■		■		■	
Seeds	■	■			■			■	
Irrigation	■	■		■	■			■	■
Chemicals	■	■		■	■	■		■	
Electricity	■	■		■					■
Materials	■	■		■		■		■	■
Feed	■	■		■		■		■	
Medicine	■	■		■	■	■		■	

Energy-Based Design Guidelines

The First Law of Thermodynamics

The first law of thermodynamics requires that energy-in equals energy-out plus any energy accumulation. The first law is the underlying basis of energy analyses—one must harvest solar energy on the farm and transport it out. One must not import and use more fossil energy than is exported as product, or the system is not operating within its energetic means and is therefore unsustainable.

Guideline 1. Maximize the accumulation of energy (stores of biological energy) on the farm.

Requirements: To get work out, a system must be out of equilibrium. This accumulation may be exported as product or used on farm to support infrastructure and processing. For instance, "fill open niches immediately" by planting or seeding, advises permaculture designer, Ben Falk (2013, 42). Allowing bare dirt means that vegetation is not growing and capturing solar energy, and bare soil is also susceptible to erosion, which could result in fertility losses and damage to waterways.

Other ways to maximize accumulation are though storing energy in fruit and nut trees, in wildlife and in animals that harvest from land that is unsuitable for production. This requires that animal and cropping systems be integrated. This guideline aligns with a guideline for "Designing Healthy and Pest-Resilient Farming Systems" listed in a Sustainable Agriculture and Research Education (SARE) publication, which advises to increase species in time and space with crop-livestock systems (Altieri, Nicholls, and Fritz 2005, 100). Schramski et al. (2013) point out that isolating plant and animal operations requires external energy to substitute the missing services that each provides the other (111). Optimizing the symbiotic relationship between plants and animals reduces fertilizer and amendment (i.e. compost) needs (Baum et al. 2009; Schramski et al. 2013), which relates to eliminating/minimizing inputs (Guideline 4). Maximizing biological energy follows the maximum power principle and is necessary to maximize productivity and feedbacks. Attention may be given to aspect too, but this is site-specific and varies with crop needs.

Considerations: The types of energy accumulation are site specific.

Relates to: Guideline 4: Eliminate/minimize inputs; Guideline 9: Account for pulsing and accumulation.

Impacts: This guideline may reduce the machinery, fuel, fertilizer, amendments, irrigation, chemicals, materials, and feed inputs needed—many resulting from healthier soils with more organic matter from integrating plants and animals. Human labor may be increased.

Historical Reference: The New Guinea villagers in Chapter Four stored biological energy in pigs, safeguarding the society from hunger during poor years. Many societies have stored energy in animals. Also, as still practiced today on many homesteads and in orchards, fruit and nut trees store energy and provide food products.

Guideline 2. Accumulate and store the rainfall energy for irrigation.

Requirements: This guideline advises storing rainwater at various locations throughout the farm and capturing potential energy in order to release and utilize the energy (using gravity) when crops need water. Figure 5.1 shows a pond dug into the side of a mountain to store water for irrigation.

Storing rainwater for irrigation is also a goal for designs outside of agriculture. Because of the ecological impacts of simply storing and utilizing rainwater on site, the Leadership in Energy & Environmental Design (LEED) Rating System rewards points in Sustainable Sites Credit 6.1 Stormwater Design—Quantity Control, Sustainable Sites Credit 6.2 Stormwater Design—Quality Control, Water Efficiency Credit 1 Water-Efficient Landscaping, and Water Efficiency Credit 3 Water Use Reduction. Therefore, in addition to reducing energy needs, this guideline also has benefits related to stormwater runoff quantity, water quality, and water use efficiency.

Considerations: The climate and topography of the particular farm determine the feasibility of this guideline. Also, livestock access to ponds can result in polluted water. A ram pump may be considered for pumping water out of reservoirs.

Relates to: Guideline 11: Maximize power across all scales

Impacts: This guideline has the capability to reduce energy put into irrigation and electricity consumption. Initially, this could increase machinery, fuel and material inputs used in the construction of reservoirs.

Historical Reference: Though not documented in any of the presented precedent studies, building reservoirs to store captured rain water uphill is a method still used today. The author witnessed this energy-reducing strategy in the remote northern hill tribes of Thailand. There, water was stored in higher elevations to be released to the rice paddies, where it flooded each terrace and flowed through check dams. In the U.S., it may be observed on Joel Salatin's Virginia farm. Salatin uses the topography of his farm to his advantage as he captures the water in uphill reservoirs and uses a small pump (operating off of fossil fuels) to pull water from the ponds, which is then distributed over his fields by gravity. One of Salatin's ponds is shown in Figure 5.1.

Figure 5.1. Picture of Stored Rainfall at Joel Salatin's Polyface Farm (Photo taken by author, 2013).

<u>Guideline 3</u>. Maximize capture of renewable energy if feasible, and only to a level that does not impede Guideline 11: Maximize power across all scales.

<u>Requirements</u>: The capture of energy should be on site or nearby to minimize losses if transmitted as electricity. Another option is harvesting the energy and transferring it directly into useable work on-site.

Considerations: Depending on region and location, this may entail harvesting wind, water, solar, geothermal or tidal energy. Where possible and if feasible, using renewable materials to construct harvesting equipment is preferable in order to reduce inputs into farm. Renewable harvesting should be site specific in order to avoid disrupting maximum power across scales (Guideline 12).

Relates to: Guideline 2: Use rainfall energy; Guideline 11: Maximize power across all scales

Impacts: This could reduce the use of fuels and electricity while initially increasing material inputs, labor and possibly machinery and fuels—depending on method.

Historical Reference: Preindustrial societies used windmills to lift water and power mills and waterwheels to saw and press oil (Smil 2008). New technologies may be developed to improve designs and make harvesting renewables more efficient and powerful while lessening the associated environmental impacts.

The 2nd Law of Thermodynamics

The Second Law requires energy losses for every energy transformation.

Guideline 4. Eliminate or minimize inputs from outside the farm.

Requirements: The second law restrains (transported) inputs to the farm. Each unnecessary energy transformation results in a loss of available, useful energy. The energy loss associated with every transformation (i.e. fossil > thermal > kinetic) limits inputs, and makes those that come from closer distances more practical. From a design standpoint, the second law requires that an energetically sustainable agricultural system have minimal off-farm inputs and operate as a closed system as much as possible, with the needs of the system being provided on the farm as a result of its functional arrangement and beneficial aspects of its stores of biological energy or vegetation. Without subsidized energy, the necessary off-farm inputs and the off-farm outputs must still be within close proximity to the farm in order to minimize energy losses. This relates to the achievable scale for low-input systems. Design Guideline 10 expands on appropriate scales. More energy is required for traveling further distances. This understanding contributes to the basis for many supporters of localized food production.

Another area in which this concept has gained attention in the past decade is in the LEED Rating System. Project design teams can earn credits for using "regional materials" that are harvested and manufactured within a 500 mile radius from the project site (LEED Reference Guide, 379). The idea is that inputs are derived locally to reduce fossil energy consumption.

Considerations: Because nutrients are exported as food, nutrients likely will have to be imported from nearby areas, but these nutrients should be of biological and not synthetic origin. Other off-site inputs are expected, but the most energy-efficient system will minimize inputs and minimize the distance from which they are acquired. Progress towards satisfying this guideline may be achieved more quickly by plant and animal operations in close proximity partnering together to reduce high embodied energy inputs shipped from hundreds of miles away.

Relates to: Guideline 10: Farm should be human-scale

Impacts: This guideline is expected to reduce machinery, fuels, fertilizers, amendments, seeds, chemicals, materials, and feed. Without machine power, labor is expected to increase.

Historical Reference: An example is the traditional Chinese system in which farmers acquired nutrients for their crops from nearby villages. In nature, animals adhere to this law, exhibited by the distance they travel to hunt for food. They are constrained within a certain spatial proximity (determined by scale of territory) in order to have a positive energy return on investment.

Guideline 5. Minimize transformations (i.e. minimize the number of steps in every process).

Requirements: This guideline relates very closely with spatial dimensions of energy hierarchy, but more specifically this guideline refers to planning for human flows throughout the farm. Ben Falk (2013) recognized this in the "Resiliency and Regeneration Design" principles in his book *The Resilient Farm and Homestead*. He noted, "moving things is entropy" (35). He made the point that some actions, such as planting a tree, offer multiple results, whereas moving something "offers little benefit except the result of a material in a new location" while requiring energy, time, and often money. Therefore, the most optimal sites "reduce wherever possible the need to move materials from one place to another" (Falk 2013, 36). This is important to consider when siting things like compost or barns. The key is minimizing transformations of human energy into work.

This guideline can be applied in other ways, too. For instance, in Chapter Three, "eating closer to the sun" is discussed because eating plants is more energy efficient than eating meat as there are energy losses involved in the transformation associated with the metabolic losses of the animal. Therefore, if the goal is to maximize the amount of energy provided to humans, in areas suitable for cultivation and without sacrificing ecological capital, design for crop rotations in order to provide the most nutrition for humans. However, this must be planned with regard to the energy hierarchy across scales (Guideline 10) to prevent imbalances between scales.

Considerations: Smil (2000) recognizes land unsuitable for crop production as semiarid grasslands, sloped land, and mountain meadows. Additionally, animals provide services for crop fields when grazing the grasses or leguminous cover crops by recycling the nutrients and improving soil quality.

Relates to: Guideline 6: Create spatial centers

Impacts: This provides an indirect energy savings impacting the amount of machinery, fuels, fertilizers, irrigation, chemicals, materials and feed inputs needed. Planning human flows is intended to directly reduce labor energy inputs.

Historical Reference: This is exhibited in the !Kung Bushmen society as the bushmen hunt first for food closest to their camp. During stressed periods, they eat less desirable foods from nearby. By doing this, the group minimizes energy transformations.

Energy Hierarchy - Spatial Patterns

Energy hierarchy is exhibited in the landscape as spatial centers. Flows from spatial centers are concentrated and spread useful work over a large territory. The territory supports the spatial centers, and the centers' feedback support to the territory. Odum (2007) uses the spatial organization of a city and its surrounding landscape to demonstrate this principle, but it is easily understood how this can be applied to a farm. A spatial center on a farm is the meeting place for workers. From the spatial center, which may not actually be in a central location on the farm, workers disperse and care for the farm. Tools go out from and back to the spatial center. It is also likely that seed is carried to the fields from the center, and the harvest is transported to the center before being eaten or transported off farm.

Guideline 6. Create spatial centers on farms, for the supporting area to feed into and from which control will feed out.

Requirements: Centralizing operations helps maximize power and helps overcome the decrease in energy occurring with each transformation according to energy hierarchy. Ideally, one farm would have one spatial center, which is supplied from smaller spatial centers. These small centers may be gathering points in fields from which workers spread out and plant, tend or harvest. These smaller centers feed into larger centers, which may be a barn located near the farmhouse. From the large spatial center, support feeds back to the smaller centers. Support could be in the form of management, seeds, nutrients, or other needs particular to farm type. Odum's graphic seen in Figure 2.7 shows spatial patterns of energy hierarchy in the landscape. Though the geography example was used in Chapter Two, this could also be a farm landscape as in Figure 5.2.

Considerations: The appropriate scale of the supporting territory (i.e. farm) is discussed in Guideline 10 and should be considered when planning spatial centers. Also, scale addresses the size of the spatial centers and structures. The location of the spatial center is addressed in Energy Convergence Guideline 12.

As mentioned in Chapter Two, geographical spatial centers are often in the form of villages, towns, and cities. City planners, transportation engineers, and others design the infrastructure, roads, and flows, but the designs have not always been consistent with energy hierarchy principles (Odum 2007). A popular idea currently is "new urbanism." Odum notes that increasing concentrations by infilling in cities "may be contrary to the need to retain small hierarchies within the pattern of large hierarchies" (Odum 2007, 343). This relates also to appropriate scale (Guideline10) and concentrating materials (Guideline 7). For existing large scale farms trying to create spatial centers to reduce energy inputs, consider the scale and maximizing functions when designing secondary and tertiary centers.

Relates to: Guideline 5: Minimize transformations; Guideline 10: Farm should be human-scale; Guideline 12: Develop near energy convergence

Impacts: Creating a spatial center on a farm is intended to reduce labor and machinery and liquid fuels (if and when used).

Historical Reference: The !Kung Bushmen hunting and gathering society and the New Guinea villagers practicing shifting agriculture both provide examples of establishing spatial centers, from which they expressed control over the territory that supported them.

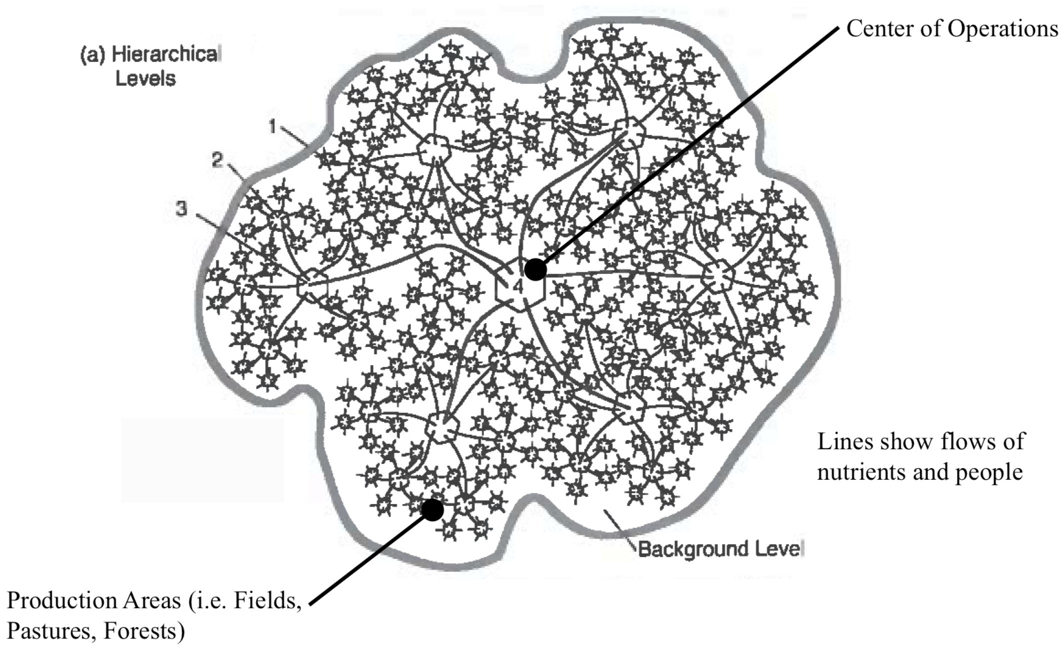

Figure 5.2. Spatial Pattern of Energy Hierarchy in an Agricultural Landscape (Adapted from Odum, 77).

Energy Hierarchy – Concentrating Materials

Energy is required to concentrate materials, people and animals. With less energy, less can be concentrated.

Guideline 7. Appropriately concentrate plants and animals throughout the landscape, such that minimal energy is required for concentration.

Requirements: This guideline is largely dependent on the type of farming and the environment in which it is taking place. The individual physiology and behavior of the plant and animal species and available resources within a system are also factors in understanding what is appropriate for a particular farm.

Considerations: Concentration of humans also requires energy, and should be considered. However, the settlement of humans in the landscape is beyond the scope of this research, though future energy shortages are projected to spur decentralization of humans (Odum and Odum 2001). Therefore, as a consequence of this energy principle, more humans may once again become integrated into the agricultural landscape.

Crop monocultures and concentrated animal feeding operations (CAFOs) are examples of energy-intensive farming techniques that this guideline will eliminate. The research and money invested in making this type of method "organic" or "sustainable" should consider this guideline and the energetic basis of it. Additionally, large-scale monoculture farms and CAFOs transitioning to a low fossil energy input system will, no doubt, have long-term planning and restructuring before an economically viable shift can be made.

This guideline should take into consideration the natural patterns of group behavior. For example, because of predator threats, cattle tend to herd together for safety. Native vegetation in forests exhibit grouping to some extent as well.

Relates to: Guideline 1: Maximize accumulation; Guideline 10: Farm should be human-scale

Impacts: This guideline could possibly increase or decrease labor, depending on system type. Direct reductions should occur in fuels, chemicals, electricity, materials, feed and medicine.

Indirect reductions in fertilizer, amendments and irrigation could stem from integrated plant and animals systems with increase soil organic matter.

Historical Reference: None of the precedent studies presented in Chapter Four appeared to have high-density concentrations of animals or vegetation.

Energy Hierarchy – Information

Information is energetically expensive—it takes a lot less emergy to copy than to create new information. Information may be biological or cultural. Copies of information may develop variations from the original depending on the local environment.

Guideline 8. Design space for the development of high-emergy information.

Requirements: This may work best in the margins of the fields as practiced in Andean agriculture (Berry 1977). Surrounding the crop in the margins, new species can develop that are successful against insects and disease. Simultaneously, the margins will capture nutrients and runoff from the fields, keeping them on the farm. For designing healthy and pest-resilient farming systems, SARE provides a similar guideline, stating, "Expand genetic diversity with variety mixtures, local germplasm and multilines (or varieties that contain several different genes for resistance to a particular pest)… that can better withstand disease and pests" (Altieri, Nicholls, and Fritz 2005, 100).

Considerations: Cultural information is important for maintaining this practice, but is beyond the scope of this research. Also, regulations currently exist on patented seeds, which many farmers use. This is also a consideration for this guideline.

Relates to: Guideline 6: Create spatial centers; Guideline 11: Maximize power across scales

Impacts: This guideline will reduce seed, fertilizers and chemical inputs.

Historical Reference: Andean agricultural societies plant crops in the field margins to be cross-pollinated by the birds and insects living in the hedgerows or nearby forests. New varieties develop there on the farm, and in the case that a disease or pest destroys a crop, the farmer may select a surviving new variety found in the field margin. This method reduces or eliminates seed input, chemicals, and fertilizers, as the variety is adapted to the soil conditions of the site on which it was developed.

Energy Hierarchy – Time and Storage

All scales across the energy hierarchy exhibit an accumulation-pulsing sequence.

Guideline 9. Account for natural pulsing by designing areas for accumulation and areas for frenzied release. This requires understanding the balance needed between the producers and consumers on the farm.

Requirements: Natural pulsing provides an energetic basis for crop and animal rotation. Farmers can maximize energy stores through timely harvests of crops and forage by understanding plant physiology and growth cycles (i.e. accumulation and pulse).

For livestock operations, this principle is acknowledged in rotational grazing by placing the livestock on forage in its optimal stage of growth. This is when it is desirable to livestock and at the time that plant growth is about to level off, therefore the most solar energy is harvested. In farm design, this requires balancing the grazing herd and grazing area to optimize use of the plant energy.

Pulsing is the energetic purpose for shifting agriculture and crop rotations. The pulse occurs as energy rich nutrients are harvested from a site, and the accumulation period is when the land is fallow, again accumulating nutrients through recycled biomass. In design, this guideline requires that fields and plots be reserved for accumulation to be followed by harvesting in order to minimize input energy. Crop rotation also benefits pest control (Pimentel et al. 1993; Altieri, Nicholls, and Fritz 2005) and helps reduce disease and weed problems (Pimentel and Pimentel 2008). The SARE guidelines for designing healthy farms reinforce this energy-based guideline when instructing to implement crop rotations, polyculture and agroforestry in order to increase species in time and space (Altieri, Nicholls, and Fritz 2005).

This guideline also applies to natural ecosystem areas, especially forested ecosystems. Depending on region, on-farm needs and forest product market, trees may be harvested to maximize energy stores of biomass in the woodlands. An understanding of the forests in a particular region and the specific tree species physiology is needed to make management decisions. However, for the farm design, Odum and Odum (2001) state that approximately 10% of land should be kept in patches or strips of mature ecosystems for long-term sustainability.

Considerations: The type of farming and environment are determining factors for the details of designing for pulsing.

Relates to: Guideline 1: Maximize accumulation

Impacts: This guideline is expected to decrease labor, fertilizers, amendments, chemicals and feed. Labor is expected to decrease due to fewer tasks of fertilizing and spraying. Material inputs may increase initially, depending on material type, if switching to a rotational grazing system.

Historical Reference: The shifting agricultural societies were, in the most basic way, responding to pulsing and accumulation.

Energy Hierarchy – Territory, Turnover Time and Transformity as a Measure of Scale

The initial input energy into a series of energy transformations impacts the transformity, and a series of transformations is essentially energy passing through scales of size over time.

Guideline 10. The scale of the farm should be human scale.

Requirements: The scale of the territory that supports the farm and to which the farm feeds back support should be such that it can be managed without fossil energy inputs.

Considerations: This guideline relates to Jackson's theory that the scale of a farm is dependent on the balance between cultural and biological information and energy. The appropriate scale of a farm is also a factor of environment and social and cultural conditions. Many factors play into this determination, but once we go beyond the human scale, a source of subsidized energy will be needed. As Berry (1977) wrote, "Past the scale of the human, our works do not liberate us—they confine us" (104). In the future, this may result in large acreages scaling down and decentralizing, as represented in Figure 5.3.

Related to: Guideline 5: Minimize transformations; Guideline 7: Design for appropriate concentration

Impacts: This guideline is expected to increase human labor if machine use is reduced. If machines are still in use, labor may be reduced. A scaled-down farm would result in reduced machinery and fuel inputs.

Historical Reference: Traditional agricultural societies in China provide an example of appropriate scale. The average "economic-sized" farm was 8 acres and the largest across several agricultural districts was 20 acres. These agricultural landscapes may contrast greatly with landscapes over the Great Plains or other regions in the U.S., so this is not to imply that 20 acres is the limit.

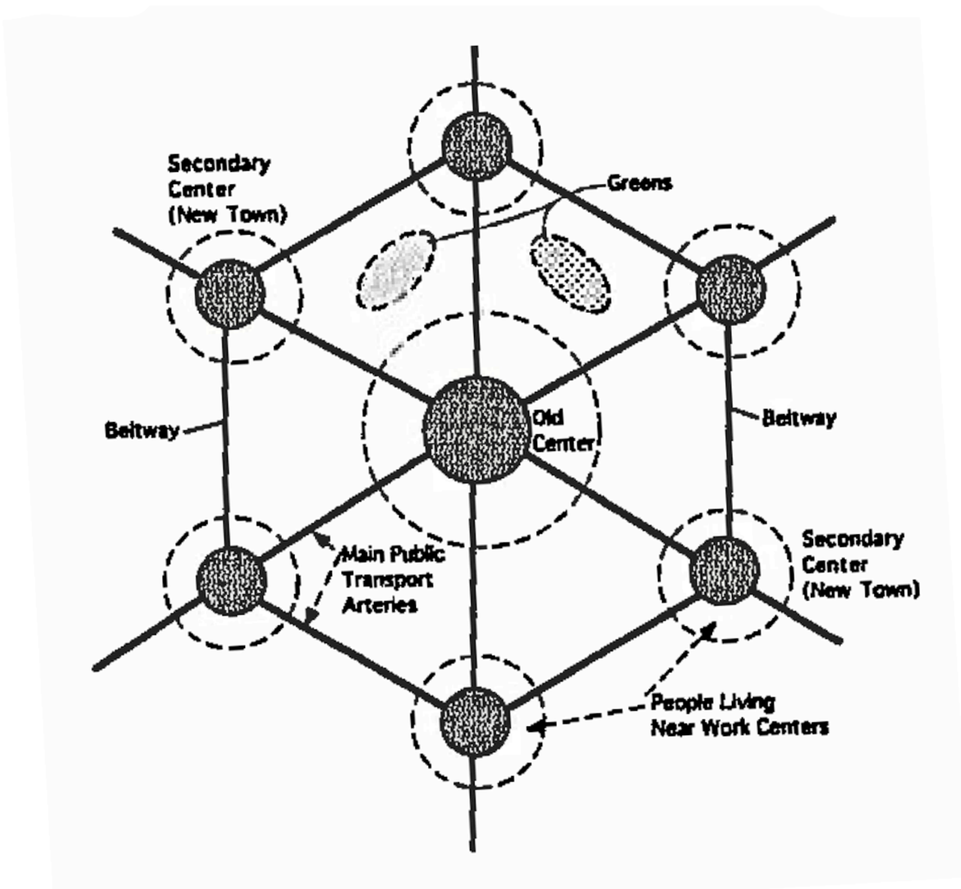

Figure 5.3. Reduction in Scale and the Decentralization of Cities. This trend is expected due to the energy intensiveness of concentrating materials. Without subsidized energy, concentration, and therefore scale, will decrease (Odum and Odum 2001, 211).

Energy Hierarchy – Across Scales

For a system to operate at maximum power, no part may take precedence over another.

<u>Guideline 11</u>. Maximize power of the system by maximizing power across all scales.

<u>Requirements</u>: This requires that each level of the energy hierarchy be part of a collective development, in which no level is given precedence over another.

<u>Consideration</u>: In the overview of modern agriculture, we see that inputs such as chemicals (i.e. herbicides, pesticides, insecticides, fungicides) and to some extent fertilizers are put into systems in order to overcome imbalances in the system. In addition to the existing imbalance, these inputs harm other levels in the system. This often increases production as long as fossil energy is abundant. Without fossil energy to supply these inputs, the system must be viewed as a whole connected bottom-up system. The plants provide energy to animals and humans, animals provide energy to humans, and plants, animals, and humans all provide energy to soil organisms in the form of residue and wastes (i.e. organic matter). Then the soil organisms mineralize the nutrients that feed the plants. Each part of the system must be balanced to maximize power across scales. Imbalance favors one level over the other, which ultimately decreases the maximum power of the system. This inherently addresses the biodiversity of a farm as many different species make up the spectrum of scales. Also, the balance is site-dependent.

A SARE guideline for designing healthy farms is a reference for this guideline. For designing healthy, pest-resilient farms, SARE recommends, "Boost soil biotic activity and improve soil structure with regular applications of organic matter" (Altieri, Nicholls, and Fritz 2005, 100). This again stresses the importance of organic matter in soil and the importance of maximizing or "feeding" all scales in the system.

<u>Relates to</u>: Guideline 8: Support the development of information; Guideline 4: Eliminate/minimize inputs

Impacts: This guideline is expected to decrease machinery, fuels, fertilizers, amendments, seeds, irrigation, chemicals and materials (i.e. plastic mulch). Labor is very likely to increase.

Historical Reference: The shifting agricultural societies exhibit an example of maximizing power across scales. These societies accounted for the mammals, birds, insects, and diseases that would reduce their yields (Pimentel and Pimentel 2008), though this is an extreme example. Traditional agriculturalists in Europe aided the microbial scale in the soil with Norfolk's four-year succession; they also farmed sheep, diversifying their operations, and allowing the animal to recycle nutrients that went back into the soil.

Energy Hierarchy – Energy Convergence

Locations of high empower within the landscape are often where civilizations originate. We have discovered how to capture energy in the landscape using technology that converts it to useful work energy for our purposes. Waterwheels and windmills initially took advantage of high-energy flows in the landscape. Now, wind turbines and hydroelectric dams harness the natural energy of the land.

Guideline 12: Site spatial centers near (or orient new development towards) centers of energy convergence, when and where appropriate.

Requirements: Desirable centers may be near flowing streams, rivers, lakes, springs, or other naturally occurring water bodies on the farm property.

Information: Assuming a farm center is already established, consideration may be given to future development closer to on-site renewable energy source if this is appropriate for the farm's operations.

This guideline is based on energy hierarchy in the landscape and the use of natural energies by preindustrial societies without fossil fuels. The form of energy harvest (i.e. windmill, waterwheel) would likely be a regional pattern. As seen in Dutch landscapes, the windmill has cultural value as well as functional. Odum and Odum (2001) projected, "When ways of life and livelihood become based once more on the very different environmental conditions in different regions, cities may be expected to regain individuality" (209).

Consideration: Consideration should be given to flood zones and extreme weather events that may impact development or overall farm operation. Traditional agricultural societies in Egypt utilized the Nile flood zone to their advantage. This method may be feasible for areas such as the Mississippi Delta, though modern landscape use and extreme events may result in destructive flooding with erosion.

Relates to: Guideline 3: Maximize renewable energy; Guideline 6: Create spatial centers

Impacts: This guideline could decrease labor, fossil-fueled machinery, fuels and electricity. It could aid in irrigation for some farms. Also, material inputs may initially be increased, though supplies may be produced on the farm.

Historical Reference: The preindustrial agricultural societies in Egypt settled and farmed near the Nile, taking advantage of the high emergy floodwaters.

Guideline Analysis

This concludes the Energy-Based Design Guidelines developed from the laws of energy for this research. The matrix below (Table 5.2) shows the inputs that the Design Guidelines are expected to impact. The impact assessment of these guidelines is difficult because the guidelines are vague concerning important factors such as the type of farm and the type of environment, and even the cultural information and management. Also, the inputs are not likely to be impacted uniformly across all systems due to the complex interaction of the various factors. Notice that all of the expected increases occur in human labor. Human labor, a form of biological energy, is renewable. This is also in line with the expectation of Odum and Odum (2001) that as high energy flows subside, human populations will decentralize throughout the landscape. Considering the unemployment rate and obesity problem in America—more than one-third of all adults are obese with a BMI>30 (Ogden et al. 2014)—this shift could lead to an increase in human health, as well as a reconnection of people to their food.

Table 5.2. Energy-Based Design Guidelines and Impacted Inputs.

	Classic Energy Laws					Fifth Law - Energy Hierarchy						
	Maximize accumulation	Use rainfall energy	Maximize renewable energy	Eliminate/minimize inputs	Minimize transformations	Create spatial centers	Design for appropriate concentration	Support the development of information	Account for pulsing and accumulation	Farm should be human-scale	Maximize power across all scales	Develop near energy convergence
Labor	Increase		Temporary Increase	Increase	Decrease	Decrease	Increase		Decrease	Increase	Increase	Decrease
Machinery	Decrease	Temporary Increase	Temporary Increase	Decrease	Decrease	Decrease				Decrease	Decrease	Decrease
Fuels	Decrease	Temporary Increase	Decrease	Decrease	Decrease	Decrease	Decrease			Decrease	Decrease	Decrease
Fertilizers	Decrease			Decrease	Decrease		Decrease	Decrease	Decrease		Decrease	
Amendments	Decrease			Decrease			Decrease		Decrease		Decrease	
Seeds				Decrease				Decrease			Decrease	
Irrigation	Decrease	Decrease			Decrease		Decrease				Decrease	Decrease
Chemicals	Decrease			Decrease	Decrease		Decrease	Decrease	Decrease		Decrease	
Electricity		Decrease	Decrease				Decrease					Decrease
Materials	Decrease	Temporary Increase	Temporary Increase	Decrease	Decrease		Decrease		Decrease		Decrease	Temporary Increase
Feed	Decrease			Decrease	Decrease		Decrease		Decrease			
Medicine							Decrease				Decrease	

Increase Expected	(red)
Decrease Expected	(green)
Temporary Increase	(yellow)

Also of consideration is the ease and speed with which these guidelines can be feasibly adapted. For instance, constructing a reservoir uphill for irrigation (Guideline 2) or locating a new (needed) barn near a spatial center (Guideline 6) is likely to be much easier than maximizing power across scales (Guideline 11). Table 5.3 shows which guidelines may be easily implemented immediately or as soon as needed, and which are more transformational and likely to require significant changes and more time to implement. Some guidelines may be both. For example, Guideline 1 (Maximize accumulation) can be easily implemented by planting fruit and nut trees in appropriate areas. On the other hand, integrating crops into animal operations or integrating animals into a cropping system is a transformational shift, which is anticipated to require a lot of planning. The type of operation and scale also influences the ease of implementation. This is represented in the matrix as some guidelines have both immediate and long-term boxes checked. An example is Guideline 11 (Maximize power across scales), which diversified, smaller farms could more readily implement (compared to a large monoculture operation).

Table 5.3. Time Frame of Guideline Adaptation.

	Classic Energy Laws					**Fifth Law - Energy Hierarchy**						
	1. Maximize accumulation	2. Use rainfall energy	3. Maximize renewable energy	4. Eliminate/minimize inputs	5. Minimize transformations	6. Create spatial centers	7. Design for appropriate concentration	8. Support the development of information	9. Account for pulsing and accumulation	10. Farm should be human-scale	11. Maximize power across all scales	12. Develop near energy convergence
Immediate	■	■	■	■	■			■	■		■	
As needed					■	■						■
Long-term	■		■	■	■	■	■	■	■	■	■	■

Many of the energy-based design guidelines align with other familiar initiatives, though the motivations behind them may be different. Perhaps this is a consequence of the multiple benefits resulting from one action. Table 5.4, below, illustrates the energy-based design guidelines that are related to or align with other initiatives.

Table 5.4. Guidelines Aligning with Other Initiatives.

	Classic Energy Laws					**Fifth Law - Energy Hierarchy**						
	1. Maximize accumulation	2. Use rainfall energy	3. Maximize renewable energy	4. Eliminate/minimize inputs	5. Minimize transformations	6. Create spatial centers	7. Design for appropriate concentration	8. Support the development of information	9. Account for pulsing and accumulation	10. Farm should be human-scale	11. Maximize power across all scales	12. Develop near energy convergence
Climate Change Adaptation		■	■		■		■	■		■		■
Green Building (LEED, SITES)	■	■	■		■	■	■					
Green Infrastructure		■										
Local Ag/Urban Ag/SARE	■	■		■	■		■	■	■	■	■	
Local Economy			■	■								
Zoning/Planning						■	■			■		■

Conclusion

The Energy-Based Design Guidelines set forth attempt to answer the question: How can the laws of thermodynamics influence landscape design and reduce direct and indirect energy inputs in rural agricultural systems to achieve energy-independence? The guidelines successfully provide an energetic-basis for design, though they fail to provide solid, exact answers that apply to any farm, anywhere. This is part of the success of a fossil-fueled agriculture—there is, for the most part, a "one-size-fits-all" answer. If the crops are not growing fast enough, add fertilizer; if bugs are eating your crop, use pesticides; and so on. Also, these guidelines only address design—management determines the success of operating a farm without fossil energy. Going into this research, this was expected.

Another expectation was that the guidelines can, in no way, assure the high production rates of modern agriculture. Again, the population is rising and people are malnourished. The "solution" to hunger or the answer to population growth, if it exists, is not an easy or straightforward one. Regarding the hunger and population issue, Daniel Hillel, who received the 2012 World Food Prize, suggested education tends to be a factor in population (Hillel, "2012 D.W. Brooks Lecture"). But presently, food is being wasted and many in the U.S. are unemployed. Perhaps replacing machine power with human power is part of a solution. Lifestyle changes are also another, and education is always a factor. The complex nature of this issue suggests that the solution will require a finding a balance of a variety of changes. Regardless, the looming energy crisis will force a change if we do not begin to adapt now and learn to balance energy flows. Schramski points out that balancing energy is critical to the future of sustainability because once energy is balanced, so many other issues are addressed—climate change, soil erosion, and deforestation, to name a few (personal communication). Much landscape architecture, agriculture, engineering, ecology, policy, economics, and marketing research should be focused on energy and addressing the root of the problem instead of just its effects. There is still much to learn.

For instance, according to the energy hierarchy of information, information contained within anthropological studies of preindustrial agriculture has the potential to contribute more helpful and, perhaps, more site-specific information to low-energy agriculture. Using knowledge gained by decades to centuries of trial-and-error consumes less energy than trying to discover information anew. Also, combining more research focused on energy, nutrient cycling, and ecosystem services could result in more encompassing design guidelines and more productive energy-independent systems. In this way, these guidelines are incomplete, though because of our limited knowledge and understanding of energy and ecosystems, no amount of research would make them "complete." However, we should not quit trying, and we should collaborate with other disciplines to find more effective approaches to solving the energy and agriculture problem. It seems that some of these guidelines are common sense, but cheap fossil fuels have skewed our society's view of energy and made it so that we forget the simple things sometimes. Or perhaps the invasiveness of fossil energy into our lives has disconnected us from understanding our energetic limitations, and our landscapes reflect that. Design is easy with fossil energy—humans can make nearly anything happen. But, without energy, we must be much more creative (Schramski, "Chapter 6: The Development of Agriculture").

Energy-based guidelines, science, and history do not contain all the answers for the design of a successful farm. Though the understanding of the physical laws of earth aid in design, the design itself is not an exact unchanging science as industrial agriculture suggests. Each farm is different, even if in the same region. Each design must be different to respond to the land and the people that live on that land, and it must be adaptive to change with both. Therefore, design guidelines must contain flexibility and be able to be adapted to different systems and different crops growing in different climates on different soils. In a conversation between the author and Wes Jackson regarding finding the right balance of cultural and biological information and farm scale, Jackson said, "it's an art." In his essay, "People, Community, and Land," Wendell Berry (1983) summarized the art of designing with nature when he wrote,

> "In a society addicted to facts and figures, anyone trying to speak for agricultural harmony is inviting trouble. The first trouble is in trying to say what harmony is. It cannot be reduced to facts and figures—though the lack of it can. It is not very visible a function. Perhaps we can only say what it may be like. It may, for instance, be like sympathetic vibration: 'The A string of a violin… it is designed to vibrate most readily at about 440 vibrations per second: the note A. If that same note is played loudly not on the violin but near it, the violin A string may hum in sympathy.' This may have a practical exemplification in the craft of the mud daubers which, as they trowel mud into their nest walls, hum to it, or at it, communicating a vibration that makes it easier to work, thus mastering their material by a kind of song. Perhaps the hum of the mud dauber only activates that anciently perceived likeness between all creatures and the earth of which they are made. For as common wisdom holds, like speaks to like. And harmony always involves such specificities of form as in the mud dauber's song and its nest, whereas information accumulates indiscriminately, like noise" (15).

This suggests that farming and design is not just a science, but much more—an art, in fact. An art that requires many years of experience and centuries of information to master, perhaps that is the key to farming with low energy inputs. It is an ongoing process of adaptation instead of a one-time design project. These energy-based design guidelines are a start towards thinking of design in energetic terms. However, it is vital that we act now and learn more from the passed down, energetically expensive information, because now we are still enjoying the benefits of fossil energy. Our children and grandchildren are not likely to have that luxury.

REFERENCES

Allison, F.E. *Soil Organic Matter and Its Role in Crop Production*. New York: Elsevier Scientific Publishing Company, 1973.

Altieri, Miguel A., Clara I. Nicholls, and Marlene A. Fritz. *Manage Insects on Your Farm*. Beltsville, MD: Sustainable Agriculture Network, 2005. Online version: http://www.sare.org/Learning-Center/Books/Manage-Insects-on-Your-Farm.

Alternative Fuels Data Center. Washington, DC: Department of Energy; [updated 2013 Feb 27; cited 2013 Dec 04] .Alternative Fuels Data Center—Fuel Properties Comparision. http://www.afdc.energy.gov/fuels/fuel_comparison_chart.pdf

"ASLA Code of Professional Ethics," American Society of Landscape Architects, Last modified November 14, 2013. Accessed March 29, 2014. http://www.asla.org/ContentDetail.aspx?id=4276&RMenuId=8&PageTitle=Leadership.

Axelsson, G. Sustainable geothermal utilization – Case histories; definitions; research issues and modelling. Geothermics, 39 (2010) 283-291. Oct. 2010.

Baum, Aaron W., Tadeusz Patzek, Martin Bender, Steve Renich, Wes Jackson. "The Visible, Sustainable Farm: A comprehensive Energy Analysis of a Midwestern Farm." *Critical Reviews in Plant Science* 28 (2009): 218-239.

Bazilevich, N.I., and L.Y. Rodin. "Geographical regularities in productivity and the circulation of chemical elements in the earth's main vegetation types." *Soviet Geography* 12, no. 1 (1971): 24-53. (CAIN719061759).

Berry, Wendell. "People, Community, and Land." *Trumpeter* 2, no. 2 (1985).

Berry, Wendell. *The Unsettling of America: Culture and Agriculture*. San Francisco: Sierra Club Books; 1977.

Buck, John Lossing. "Fact and Theory about China's Land." *Foreign Affairs* 28 (1949): 92-101. Academic Search Complete (522916735).

Buck, John Lossing. *Land Utilization in China*. Chicago: University of Chicago Press, 1937.

Butzer, Karl W. *Early Hydraulic Civilization in Egypt: a study in cultural ecology*. Chicago: University of Chicago Press, 1976.

Butzer, Karl W. "Long-term Nile flood variation and political discontinuities in Pharaonic Egypt." In *From Hunters to Farmers*, edited by J. Desmond Clark and Steven A. Brandt, 103-112. Berkeley: University of California Press, 1984.

Cardwell, Diane. "Intermittent Nature if Green Power Is Challenge for Utilities." *New York Times*, August 14, 2013. http://www.nytimes.com/2013/08/15/business/energy-environment/intermittent-nature-of-green-power-is-challenge-for-utilities.html.

Campbell, D.L. and M. Overton. "A New Perspective on Medieval and Early Modern Agriculture: Six Centuries of Norfolk Farming c.1250-c.1850." *Past & Present* 141 (1993): 38-105. Historical Abstracts with Full Text (9408031101).

Çengel, Yunus A. and Michael A. Boles. *Thermodynamics: An Engineering Approach, Fifth Edition*. Boston: McGraw Hill, 2006.

Clark, E.H. "Soil Erosion: Off-site Environmental Effects." In *Agricultural Soil Loss: Processes, Policies, and Prospects*, edited by John H. Harlin and Gigi M. Berardi, 59-89. Boulder: Westview Press, 1987.

Cordell, D., and Stuart White. Sustainable Phosphorus Measures: Strategies and Technologies for Achieving Phosphorus Security. Agronomy 2013, 3, 86-116. Published 31 Jan 2013.

Defne, Zafer, Kevin A. Haas, and Hermann M. Fritz. "Wave power potential along the Atlantic coast of the southeastern USA." *Renewable Energy* 34 (2009): 2197-2205.

Downing, Andrew Jackson. Edited by George W. Curtis. *Rural Essays*. New York: G.P. Putnam & Co., 1853.

Falk, Ben. *The Resilient Farm and Homestead*. White River Junction, VT: Chelsea Green, 2013.

Food and Agriculture Organization of the United Nations. "Food energy – methods of analysis and conversion factors." Rome: Food and Agriculture Organization of the United Nations, 2002. http://www.fao.org/uploads/media/FAO_2003_Food_Energy_02.pdf.

Food and Agriculture Organization of the United Nations. *The State of Food Security in the World 2013*. Rome: Food and Agriculture Organization of the United Nations, 2013.

Giampietro, M., K. Mayumi, and A.H. Sorman. "Assessing the quality of alternative energy sources: Energy Return on the Investment (EROI), the Metabolic Pattern of Societies and Energy Statistics." (2010). http://www.recercat.cat//handle/2072/47934.

Glaze, L.E. United States Department of Justice Bureau of Justice Statistics. "Correctional Populations in the United States, 2009." December 2010. http://www.bjs.gov/content/pub/pdf/cpus09.pdf.

Glaze, L.E. and E.J. Herberman. United States Department of Justice Bureau of Justice Statistics. "Correctional Populations in the United States, 2012." December 2012. http://www.bjs.gov/content/pub/pdf/cpus12.pdf.

Gray, D.M., and A.T. Leiser. *Biotechnical Slope Protection and Erosion Control*. New York: Van Nostrand Reinhold Company, 1982.

Gunders, Dana. "Wasted: How America Is Losing Up to 40 Percent of Its Food from Farm to Fork to Landfill." *NRDC Issue Paper* 12-06-B, (2012).

Hahnlein, S., Bayer, P., Ferguson, G. and Philipp Blum. Sustainability and policy for thermal use of shallow geothermal energy. Energy Policy 59 (2013) 914-925.

Hart, K and D. Pimentel. "Public Health and Costs of Pesticides." In *Encyclopedia of Pest Management*, edited by D. Pimentel, 677-679. NewYork: Marcel Dekker, 2002.

Hillel, Daniel. "2012 D.W. Brooks Lecture" Lecture, University of Georgia, Athens, Georgia, November 08, 2012.

"How Much Degrowth is Enough?" 2012. YouTube video, 15:31. Posted by "Jack Alpert". September 2012. https://www.youtube.com/watch?v=fcQYI4yo8mM.

Jackson, Wes. "A Search for the Unifying Concept for Sustainable Agriculture." In *Meeting the Expectations of the Land: Essays in Sustainable Agriculture and Stewardship*, edited by Wes Jackson, Wendell Berry, and Bruce Colman, 208-229. San Francisco: North Point Press, 1984.

Jackson, Wes. *Consulting the Genius of the Place: An Ecological Approach to a New Agriculture*. Berkeley: Counterpoint, 2010.

Jarvis, R.S. and M.J. Woldenburg. *River Networks, Benchmark Papers in Geology #80*. Stroudsburg, PA: Hutchinson Ross, 1984.

Kubiszewski, I., Cleveland, C.J., and P.K. Endres. "The Encyclopedia of Earth" *Energy return on investment (EROI) for wind energy*. 2013. http://www.eoearth.org/view/article/152560/. (24 April 2014).

Lee, R.B. "!Kung Bushman subsistence an input-output analysis." In *Environment and Cultural Behavior: Ecological Studies in Cultural Anthropology*, edited by A.P. Vayda, 47-79. New York: Natural History Press, 1969.

LEED Reference Guide for Green Building Design and Construction. Washington D.C.: U.S. Green Building Council, 2009.

Leonard, J.N. *The First Farmers*. The Emergence of Man Series. New York: Time-Life Books, 1973.

Leopold, L.B. and W.B. Langbein. "The concept of entropy in landscape evolution." United States Geological Survey Professional Paper 500-A. Washington D.C.: United States Government Printing Office, 1962. http://pubs.usgs.gov/pp/0500a/report.pdf.

Lindsay, R.B. *Applications of Energy: Nineteenth Century*. Stroudsburg, Pennsylvania: Dowden, Hutchinson and Ross, 1976.

Lopez, Anthony, Billy Roberts, Donna Heimiller, Nate Blair, and Gian Porro. "U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis." *National Renewable Energy Laboratory*. July 2012. <http://www.nrel.gov/docs/fy12osti/51946.pdf> (20 May 2014).

Lotka, Alfred J. *Elements of Physical Biology*. Baltimore: Williams & Wilkins Company, 1925.

Lough, Thomas S. "Energy, Agriculture, Patriarchy and Ecocide." *Human Ecology Review* 6, no. 2 (1999): 100-111, Environment Complete (8412190).

Lovins, Amory B. and Rocky Mountain Institute: *Reinventing Fire: Bold Business Solutions for the New Energy Era*. White River Junction, Vermont: Chelsea Green Publishing, 2011.

MacKay, David J.C. *Sustainable Energy—without the hot air* (Cambridge, England: UIT Cambridge Ltd.; 2009).

Markussen, Mads V., and Hanne Ostergard. Energy Analysis of the Danish Food Production System: Food-EROI and Fossil Fuel Dependency. Energies, Aug 2013.

Massachusetts Institute of Technology. "The Future of Geothermal Energy." 2006. http://geothermal.inel.gov/publications/future_of_geothermal_energy.pdf.

McDonough, William, and Michael Braungart. *Cradle to Cradle*. New York: North Point Press, 2002.

McHarg, Ian L. *Design with Nature*. Garden City, New York: the Natural History Press, 1969.

McKelvey, V.E. "Mineral Resource Estimates and Public Policy: Better methods for estimating the magnitude of potential mineral resources are needed to provide the knowledge that should guide the design of many key public policies." *American Scientist* 60, no. 1 (1972): 32-40. JSTOR Journals (edsjsr.27842943)

Mulvaney, R.L., Khan, S.A., and C.S. Mulvaney. Nitrogen fertilizers promote denitrification. Jan 17, 1996. Copyright Springer-Verlag 1997. Biology and Fertility of Soils (1997) 24:211-220. Pg 219.

National Oceanic and Atmospheric Administration. "Trends in Atmospheric Carbon Dioxide." Accessed: July 13, 2014. http://www.esrl.noaa.gov/gmd/ccgg/trends/.

Odum, Howard T. *Environment, Power, and Society for the Twenty-First Century*. New York: Columbia University Press, 2007.

Odum, Howard T., and Elisabeth C. Odum. *A Prosperous Way Down*. Boulder, CO: University Press of Colorado. 2001.

Ogden, C. L., M.D. Carroll, B. K. Kit, and K.M. Flegal. "Prevalence of Childhood and Adult Obesity in the United States, 2011-2012." *The Journal of the American Medical Association* 311, no. 8 (2014): 806-814. doi: 10.1001/jama.2014.732.

Perfecto, Ivette, John Vandermeer and Angus Wright. *Nature's Matrix: Linking Agriculture, Conservation, and Food Sovereignty*. Sterling, VA: Earthscan, 2009.

Pimentel, D., C. Harvey, P. Resosudarmo, K. Sinclair, D. Kurz, M. McNair, S. Crist, L. Shpritz, L. Fitton, R. Saffouri, and R. Blair. "Environmental and Economic Costs of Soil Erosion and Conservation Benefits." *Science* 267 (1995): 1117-1123. GeoRef, EBSCOhost (1995-027218).

Pimentel, D. and D. Wen. "Technological changes in energy use in U.S. agricultural production." In *Agroecology*, edited by C.R. Carrol, J.H. Vandermeer, and P.M. Rosset, 147-164. New York: McGraw Hill, 1990.

Pimentel, D., H. Acquay, M. Biltonen, P. Rice, M. Silva, J. Nelson, V. Lipner, S. Giordano, A. Horowitz, and M. D'Amore. "Assessment of environmental and economic impacts of pesticide use." In *The Pesticide Question: Environment, Economics and Ethics*, edited by D. Pimentel and H. Lehman, 47-84. New York: Chapman and Hall, 1993.

Pimentel, D., R. Doughty, C. Carothers, S. Lamberson, N. Bora, K. Lee. "Energy Inputs in Crop Production in Developing and Developed Countries." In *Food, Energy, and Society: Third Edition*, edited by David Pimentel and Marcia H. Pimentel, 137-159. Boca Raton, FL: CRC Press. 2008.

Pimentel, David. "Impacts of Organic Farming on the Efficiency of Energy Use in Agriculture." *The Organic Center*, 28 (2006). http://organic-center.org/reportfiles/EnergyReport.pdf.

Pimentel, David, and Marcia H. Pimentel. *Food, Energy, and Society: Third Edition*. Boca Raton, FL: CRC Press. 2008.

Pirog, Rich, and Andrew Benjamin. "Checking the food odometer: Comparing food miles for local versus conventional produce sales to Iowa institutions." *Leopold Center for Sustainable Agriculture, Ames, Iowa* 5 (2003). https://www.leopold.iastate.edu/sites/default/files/pubs-and-papers/2003-07-checking-food-odometer-comparing-food-miles-local-versus-conventional-produce-sales-iowa-institution.pdf.

Pretty, Jules, William J. Sutherland, Jacqueline Ashby, Jill Auburn, David Baulcombe, Michael Bell, Jeffrey Bentley, Sam Bickersteth, Katrina Brow, Jacob Burke, Hugh Campbell, Kevin Chen, Eve Crowley, Ian Crute, Dirk Dobbelaere, Gareth Edwards-Jones, Fernando Funes-Monzote, H. Charles J. Godfray, Michel Griffon, and Phrek Gymantisiri. "The Top 100 Questions of Importance to the Future of Global Agriculture." *International Journal of Agricultural Sustainability* 8, no. 4 (2010): 219-236. doi: 10.3763/ijas.2010.0534.

Rappaport, R.A. "The Flow of Energy in an Agricultural Society." *Scientific American* 224, no. 3 (1971): 116-132. EBSCHOhost (20963258)

Salatin, Joel. *Salad Bar Beef*. Swoope, Virginia: Polyface Inc., 1995.

Schnepf, R. "U.S. Farm Income." *Congressional Research Service*, February 28, 2014. Accessed June 30, 2014. http://www.fas.org/sgp/crs/misc/R40152.pdf.

Schramski, J.R. "Chapter 2: Planetary Energetics." Lecture, University of Georgia, Athens, Georgia, August 22, 2013.

Schramski, J.R. "Chapter 6: The Development of Agriculture." Lecture, University of Georgia, Athens, Georgia, September 26, 2013.

Schramski, J.R. "Fossil Fuel Civilization: Patterns and Trends." Lecture, University of Georgia, Athens, Georgia, November 12, 2013.

Schramski, J.R., K.L. Jacobsen, T.W. Smith, M.A. Williams, T.M. Thompson. "Energy as a potential systems-level indicator of sustainability in organic agriculture: Case study model of a diversified, organic vegetable production system." *Ecological Modelling* 267, (2013): 102-114. Science Citation Index (000324656600010)

Schwartz, M., D. Heimiller, S. Haymes, and W. Musial. *Assessment of Offshore Wind Energy Resources for the United States*. Golden, CO: National Renewable Energy Laboratory, 2010. http://www.nrel.gov/docs/fy10osti/45889.pdf.

Smil, Vaclav. *Energy in Nature and Society: General Energetics of Complex Systems*. Cambridge, Massachusetts: The MIT Press, 2008.

Smil, Vaclav. *Feeding the World: A Challenge for the Twenty-First Century*. Cambridge, Massachusetts: The MIT Press, 2000.

Smil, Vaclav. "Harvesting the Biosphere: The Human Impact." *Population and Development Review* 37, no. 4 (2011): 613-636. doi: 10.1111/j.1728-4457.2011.00450.x.

Smil, Vaclav. *Harvesting the Biosphere: What We Have Taken from Nature*. Cambridge, Massachusetts: The MIT Press, 2013.

Sosnoskie, Lynn M. and A. Stanley Culpepper. "Glyphosate-Resistant Palmer Amaranth (Amaranthus palmeri) Increases Herbicide Use, Tillage, and Hand-Weeding in Georgia Cotton. *Weed Science* 62, no. 2 (2014): 393-402. doi: http://dx.doi.org/10.1614/WS-D-13-00077.1.

Stremke, Sven and Andy van den Dobbelsteen. *Sustainable Energy Landscapes: Designing, Planning, and Development*. New York: CRC Press, 2013.

Sullivan, J. L., C. E. Clark, J. Han, and M. Wang, Energy Systems. 2010. "Life-Cycle Analysis Results of Geothermal Systems in Comparison to Other Power Systems." doi:10.2172/993694. http://www.osti.gov/scitech/servlets/purl/993694.

Thompson, William J., and Kim Sorvig. *Sustainable Landscape Construction: A Guide to Green Building Outdoors*, 2e. Washington: Island Press, 2008.

Tufts, Melissa C. "The Geography of Somewhere: A Treatise on the Theory and Practice of Landscape Architecture Adapted to the North Georgia Piedmont." Masters thesis, University of Georgia, 2008.

United States Census Bureau. "Growth in Urban Population Outpaces Rest of Nation, Census Bureau Reports." *United States Census Bureau*, March 26, 2012. https://www.census.gov/newsroom/releases/archives/2010_census/cb12-50.html

United States Census Bureau. "International Data Base World Population: 1950-2050." Last modified August 2012. Accessed November 18, 2013. http://www.census.gov/population/international/data/idb/worldpopgraph.php.

United States Census Bureau. "Urban and Rural Population: 1900-1990." October 1995. https://www.census.gov/population/censusdata/urpop0090.txt.

United States Census Bureau. "U.S. and World Population Clock." Last modified November 18, 2013. Accessed November 18, 2013. http://www.census.gov/popclock/.

United States Department of Agriculture Economic Research Service. "Farm Income and Wealth Statistics." Last modified February 11, 2014. Accessed February 14, 2014. http://www.ers.usda.gov/data-products/farm-income-and-wealth-statistics/net-cash-income.aspx#.Uv4lOvZuo7A.

United States Department of Energy. "New Wind Resource Maps and Wind Potential Estimates for the United States." WindExchange. Last modified May 1, 2014. Accessed May 20, 2014. http://apps2.eere.energy.gov/wind/windexchange/filter_detail.asp?itemid=2542.

United States Department of Energy National Renewable Energy Laboratory. "NREL Releases Estimate of National Offshore Wind Energy Potential." *National Renewable Energy Laboratory*, September 10, 2010. http://www.nrel.gov/news/press/2010/885.html.

United States Department of Energy Energy Information Administration. Independent Statistics and Analysis. "Annual Energy Review: Petroleum and Other Liquids Overview, 1949-2011." Accessed May 20, 2014. http://www.eia.gov/totalenergy/data/annual/pdf/sec5_6.pdf.

United States Department of Labor. Bureau of Labor Statistics. "Civilian Noninstitutional Population and Associated Rate and Ratio Measures for Model-Based Areas." April 2014. http://www.bls.gov/lau/rdscnp16.htm.

United States Department of Labor. Bureau of Labor Statistics. "Labor Force Statistics from the Current Population Survey: Employment status of the civilian noninstitutional population, 1943 to date." Accessed May 14, 2014. http://www.bls.gov/cps/cpsaat01.pdf.

Waterbury, John. *Hydropolitics of the Nile Valley*. Syracuse: Syracuse University Press, 1979.