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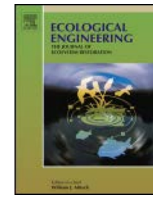

Sustainability and place: How emerging mega-trends of the 21st century will affect humans and nature at the landscape level

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ABSTRACT

We discuss the sustainability of natural and human systems in the United States in relation to 21st century threats associated with energy scarcity, climate change, the loss of ecosystem services, the limitations of neoclassical economics, and human settlement patterns. Increasing scarcity and the decreasing return on investment for existing conventional energy reserves are expected to significantly reduce the amount of affordable energy for societal needs and demands. This will also make dealing with the predicted impacts of climate change more difficult and expensive. Climate change will threaten the present sustainability of natural environments, agriculture, and urban areas but these impacts will manifest themselves differentially across the landscape. The impacts of projected climate change will make living in arid regions of the southern Great Plains, the Southwest, and the southern half of California increasingly difficult. Accelerated sea-level rise and increased frequency of strong hurricanes will increase the vulnerability of natural and human systems along the Gulf and Atlantic coasts while making them less sustainable. Ecosystem services provided by natural environments form the basis for the human economy everywhere and are also at risk from climate change impacts and overuse. Decreasing energy availability, climate change, and continued degradation of ecosystem services are likely to make continued economic growth difficult if not impossible. The capacity of neoclassical economics to effectively deal with these growing threats is limited. The areas of the country most compromised by these 21st century trends are likely to be the southern Great Plains, Southwest, southern California, the Atlantic and Gulf coasts, and densely populated areas everywhere, but especially in the northeast, Midwest, and southern California.

1. Introduction

Sustainability is the ability of a system to maintain functioning over an extended period of time. It depends upon the continuous availability of the materials and energy required to maintain system functioning and the ability of the surrounding environment to assimilate wastes from the system. The term has been adopted widely over the last 25 years as the ongoing debate about the earth's capacity to support the population and level of economic activity has developed (Gregory et al., 2009; Burger et al., 2012).

Trends relating to energy scarcity, climate change, economics, population, and ecosystem services will have to be factored into considerations of environmental and social sustainability (e.g. Day et al., 2009; Burger et al., 2012). These trends will combine to differentially affect sustainability across the landscape. Since the availability of resources (materials and energy) is limited and also not distributed homogenously over the landscape, the sustainability of cities and regions is dependent on both locally available and imported resources. Some regions have abundant natural resources (e.g. generally the eastern half of the U.S.), while others (the Southwest and northwestern Mexico) have fewer local resources, especially fertile soil and adequate water. Regions with high ecosystem services have a larger carrying capacity and natural advantage over those with low ecosystem services although these services would be compromised if more people live there.

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Most settlement in North America prior to the industrial revolution was in resource rich areas. This abundance of resources provided for growth of population and local economies and yielded a surplus that could be exported to outside markets in return for non-locally available goods and money. After the industrial revolution, fossil fuels were critical to the economy generally, but especially for development in resource poor areas. The growth of the fossil fuel industries, in combination with the development of transport and agriculture infrastructure and technology, allowed the widespread distribution of goods and services across the landscape and the development of the modern global economy. The maintenance of this system requires high material and energy throughput. Emerging energy scarcity, climate impacts, and degradation of natural systems threaten the sustainability of modern technological society, especially in areas with low natural resources.

The objective of this paper is to consider how these emerging megatrends of the 21st century will affect differentially the sustainability of cities and regions of the U.S. at the landscape level.

2. Regional impacts of climate change

Global climate change due to increased concentrations of greenhouse gases, primarily CO_2, is projected to have profound impacts over the middle section of North America in the 21st century. But these impacts will impact the landscape unevenly (U.S. Global Change Research Program, 2009). Impacts include increased temperature, changes in precipitation, accelerated sea-level rise, widespread melting of snow and ice, changes in strong storms, and more erratic weather patterns Intergovernmental Panel on Climate Change, (IPCC, 2007). In May 2013, the CO_2 concentration at the Mauna Loa observatory reached 400 ppm, a 40% increase over preindustrial levels of about 280 ppm (IPCC, 2007). Concentrations have not been this high for over 3 million years, before humans evolved.

There has been a global increase in temperature of about 1 °C over the past century and temperatures are predicted to rise from 1 °C to 5 °C during the 21st century (IPCC, 2007, Fig. 1a). Nine of the ten warmest years in the last century were in the last decade (NOAA/NASA, 2013). This warming has led to decreases in Arctic sea ice and the Greenland ice cap, worldwide retreat of glaciers, melting of permafrost, and sea-level rise.

Climate change is projected to have impacts on precipitation patterns and freshwater availability. Average annual precipitation varies greatly in the United States. In general, the 100th meridian divides the U.S. into a moist eastern half and a dry western half (Fig. 1b). Exceptions to dryness in the west are in higher elevation areas and the northwest. Most of the western U.S. has precipitation less than 50 cm/yr while the highest precipitation in the country occurs in the northwest and along the north central Gulf coast. Climate projections predict both increases and decreases in precipitation (IPCC, 2007; U.S. Global Change Research Program, 2009). The southern Great Plains and the southwest are projected to have decreased freshwater availability from 10% to 50%. The upper Mississippi and Ohio valleys and the northeast are projected to have 5% to 20% increases in precipitation leading to increased Mississippi River discharge.

2.1. Drying and the southwest

The region that is projected to experience the severest climate change impacts is the Southwest. This, the driest and hottest region of the country, is projected to become drier and hotter with greater evaporation and more extremes of both rainfall and droughts (DeBuys, 2011). These conditions are leading to more tree death, super forest fires, loss of species, and more dust in the atmosphere (Williams et al., 2012). Increasing temperatures are leading to more winter precipitation falling as rain rather than snow leading to higher stream flow in the winter and spring and less in summer months. This affects both natural ecosystems and human uses of water. Along the west coast of the U.S., summer water use is strongly dependent on snow melt as reservoirs are sized for slowly melting snow pack. This problem becomes increasingly more acute to the south because of increasing aridity and higher water demand.

The most important river for human use in the Southwest is the Colorado with a watershed covering almost 650,000 km^2 or about 8% of the lower 48 states. Discharge of the Colorado is projected to decrease by 5% to 20% by 2050 or more by 2100 (DeBuys, 2011). Lake Meade is at less than 50% capacity, and recent studies predict it has a 50% chance of drying up within two decades or less as a result of reduced river discharge and increasing evaporation and consumption (Barnett and Pierce, 2008). It is likely that Lake Mead will rarely if ever refill to capacity again.

2.2. More water and the Mississippi basin

In general, the Mississippi basin is wet and discharge averages about 18,000 m^3/s (the 8th largest discharge in the world) compared to 550 m^3/s for the Colorado. The Mississippi drains an area of 3.2 million km^2, the world's fifth-largest drainage basin. The basin is about five times larger than the Colorado basin, but discharges 32 times as much water, a reflection of the higher precipitation over the Mississippi drainage.

In 2011, there was record flooding on the Mississippi. The factors that led to the flood are all consistent with climate change projections. The intense storms that delivered so much precipitation are largely due to the interaction of warm Gulf air masses and colder continental air masses (Min et al., 2011; Pall et al., 2011). And given the trajectory of rainfall intensity in the upper basin, floods like those in 2011 are likely to become more common.

2.3. Rising sea level and stronger hurricanes in coastal zones

One of the most important climate impacts is accelerating sea-level rise. Sea level rose 15–20 cm during the 20th century (Gornitz et al., 1982; Meehl et al., 2007; FitzGerald et al., 2008) and is likely to rise a meter or more by 2100 (Pfeffer et al., 2008; Vermeer and Rahmstorf, 2009; Moser et al., 2012, Fig. 1c). Sea-level rise on the east coast is accelerating at 3–4 times the global rate (Sallenger et al., 2012).

Recent reports have indicated that hurricane intensity is related to warming of the surface waters of the ocean (Emanuel, 2005; Webster et al., 2005; Hoyos et al., 2006; Elsner et al., 2008) and that stronger storms will increase in frequency (Bender et al., 2010). Knutson et al. (2010) concluded that warming will cause the globally averaged intensity of tropical cyclones to increase. Eight of the nine costliest Atlantic hurricanes in the U.S. have occurred since 2000 (NOAA, 2011; Blake et al., 2013). Hurricanes Katrina in 2005, Irene in 2011, and Sandy in 2012 perhaps exemplify the future of the Gulf and Atlantic coasts with respect to hurricanes. Katrina made landfall in late August 2005 as a Category 3 storm (it had reached Category 5 in the open Gulf) with 194 km/h winds and a nearly 10 m surge near the Louisiana–Mississippi border (Day et al., 2007). Sandy made landfall as a post tropical cyclone. Water levels reached nearly 5 m at Battery Park in Manhattan. Storm surge during Sandy was 3.86 m at Kings Point on the North Shore of Long Island, and storm tides (storm surge + astronomical tide) reached record levels throughout the New York City area (Blake et al., 2013).

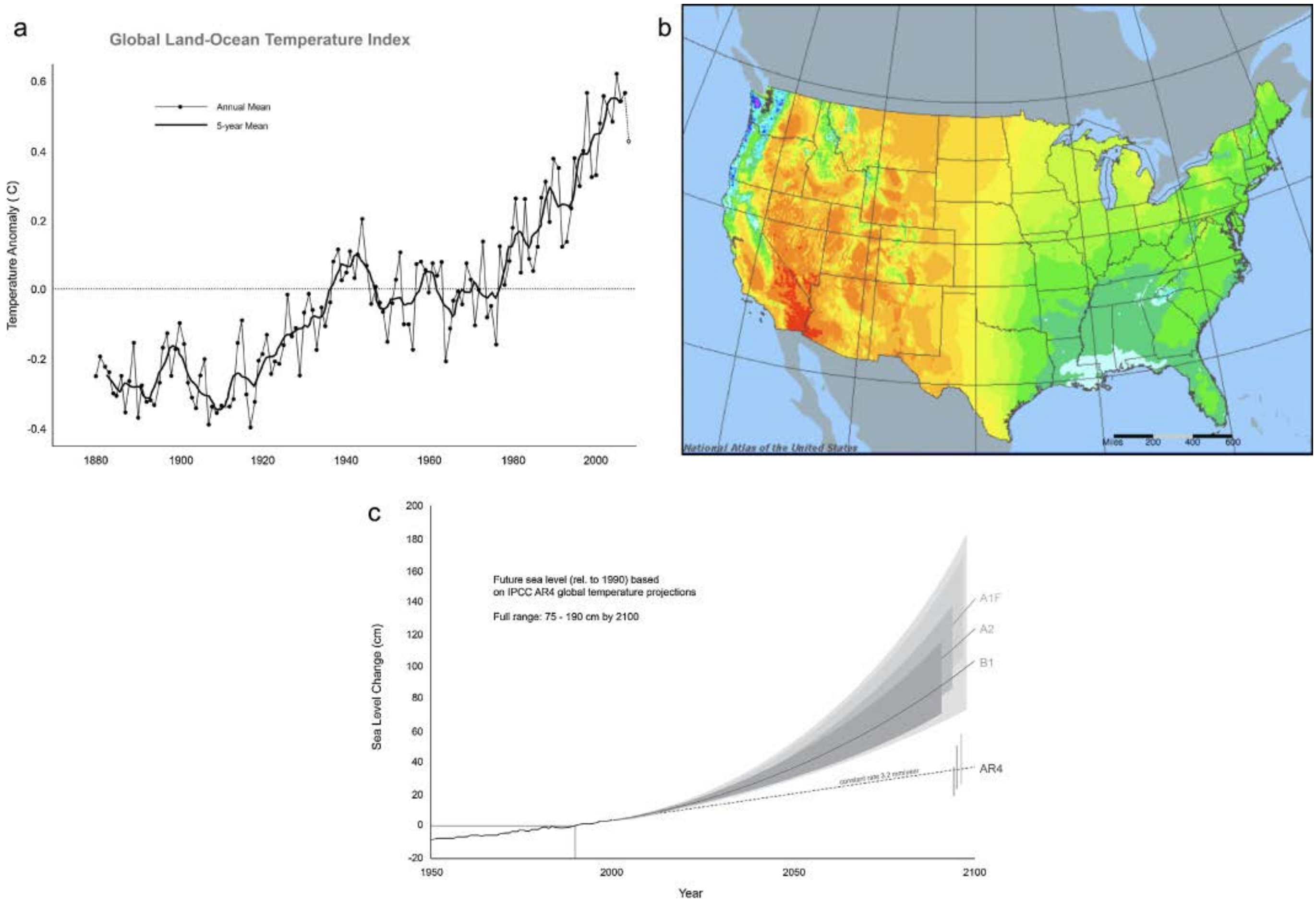

Fig. 1. (a) Global mean surface temperature change, 1880–2010 (USGCRP 2009). (b) Average precipitation patters for different regions of the U.S. The 100 meridian running from west central Texas north to the Dakotas generally separates a moist eastern U.S. from a dry western region. Red < 12 cm/yr, light blue to dark blue > 125 cm/yr (National Atlas of the United States, 2013). (c) Sea-level rise estimates for the 21st century (from Vermeer and Rahmstorf, 2009, reprinted by permission).

Storm damage from Sandy was estimated at about $50 billion, making it one of the most costly storms since 1900 (Blake et al., 2013).

Climate change in the form of sea-level rise and hurricanes will impact strongly the Gulf and Atlantic coasts. Every major city on these coasts has substantial areas near sea level. Given that hurricane surge can be as high as 5 m to 10 m, significant portions of densely populated areas are threatened. New Orleans is the worst case with 80% of the city below sea level. The city has over 500 km of levees but no other area has flood protection anything like New Orleans. It would be very expensive to build and maintain effective flood control systems for all coastal cities threatened by sea-level rise and hurricanes.

2.4. Weather extremes

Projected global climate change will lead to more extreme weather events including droughts, floods, extremely heavy precipitation, strong storms such as hurricanes, and heat waves. These conclusions were presented in a recent report by the IPCC on global warming and extreme weather that predicted heat waves that currently occur once in a generation will occur every 5 years on average by mid-century and every 2 years by the end of the century (IPCC, 2012). In some areas, heat waves will be annual events and will become hotter. Storms with very heavy rainfall will happen much more frequently. Paradoxically, melting of Arctic sea ice is leading to harsher winter weather in the U.S. and Europe (Greene, 2012).

In summary, the scientific evidence for climate change is compelling and human activity is thought by many to be largely responsible. The impacts of climate change will affect the landscape differentially. The area that will likely be most negatively affected is the Southwest including much of California and the southern Great Plains. The region will dry and there will be less water available even as the population of the area is projected to continue increasing (U.S. Global Change Research Program, 2009; Regional Plan Association, 2009). It is difficult to see how the region can adjust to these severe changes. Gulf and Atlantic coastal regions will be impacted by accelerating sea-level rise and more intense hurricanes. The Mississippi delta and southern Florida will likely be most strongly impacted but all of the Gulf and Atlantic coasts will experience large climate impacts. Unlike the Southwest, there are things that can be done to partially mitigate these impacts. People can move away from the coast and build higher and stronger. In the Mississippi delta, the resources of the river can be used to rebuild and restore the rich natural systems of the area.

3. Energy scarcity

The availability and cost of energy will become an important factor affecting the sustainability of cities and regions in the 21st century.

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3.1. Historical trends of conventional oil production

Increasing information now suggests that world conventional oil production has peaked or at least reached an undulating plateau (Campbell and Laherrere 1998; Deffeyes, 2001; Hall et al., 2003; Aleklett, 2012). Production has been on a plateau since 2005 (Bentley, 2010) and recent additions to reserves have come in the form of expensive unconventional sources that are barely keeping up with the present global decline rates for conventional oil.

Oil discoveries in an area generally precede peak production by 30–40 years. For example, U.S. oil discovery peaked about 1940 and production peaked in 1970. World conventional oil discoveries peaked by 1970 and have been falling since, despite increased drilling efforts (Campbell and Laherrere, 1998; ASPO, 2008, Fig. 2a) and most estimates of ultimately recoverable conventional oil have been about 2 trillion barrels (Hall et al., 2003). Production is now 2–3 times the discovery rate, and about 45% of current production is from the 45 largest oil fields, most of which are 30 to 40 years old. Four hundred or so giant fields, most discovered before 1960, provide about 80% of the world's petroleum (Skrebowski, 2004). About a quarter of these are declining at about 4% annually. This comes at a time when world oil demand is increasing, especially in China and India.

3.2. The potential for unconventional oil and gas

The Alberta tar sands, Bakken shale oil in North Dakota, and other unconventional sources have contributed to production increases in North America since 2005. The run-up in the price of oil over the last decade has made these sources more economic. The price of a barrel of oil increased from less than $20 in 1998 to an all time high of $147 in July 2008 (U.S. EIA, 2011) and is now above $100/barrel. Stagnating oil supply growth was one of the factors that led to this run-up in oil prices (Hamilton, 2009). The price increase has made unconventional sources economically attractive although many of these resources were identified before the 1950s (Maugh, 1978; Murphy and Hall, 2011). However, shale oil and gas have very high depletion rates and the production of unconventional reserves such as the Canadian and Venezuelan tar sands are extremely unlikely to be scaled up sufficiently to offset conventional decline rates (CAPP, 2011; Murray and King, 2012; Hughes, 2013). Tar sands oil is of a lower quality than conventional crude and this deficiency requires greater energy and financial investment to refine which is accompanied by increased levels of pollution.

3.3. Net energy yields of different energy sources

Net energy yield is the amount of energy output left over after the costs of getting that energy are factored in (Odum, 1973; Cleveland et al., 2000). This is usually expressed as energy return on investment (EROI)—which is the amount of energy returned to society divided by the amount of energy used to get that energy (Hall et al., 1979, 1986; Cleveland et al., 1984, Fig. 2b). The shift to lower EROI fuels follows David Ricardo's best first principle of resource extraction where the best, most accessible resources are extracted and used prior to the more difficult to access, lower quality fuels. Unconventional sources generally provide lower net energy than most of the conventional reserves produced up until now (Hall and Day, 2009; Murphy and Hall, 2010). As conventional oil sources are exhausted, unconventional oil sources will make up a greater proportion of supply as nationalized oil companies and corporations attempt to offset conventional oil depletion (IEA, 2012). Production is also moving into more extreme environments such as the Arctic and ultra-deepwater in pursuit of additional reserves that are more energy intensive to produce and thus have a lower EROI (Krajick, 2007; Kerr, 2010; Tainter and Patzek, 2011; Moerschbaecher and Day, 2011).

3.4. Impacts of energy scarcity

The trends toward greater reliance on energy from unconventional sources and more extreme environments are important to society. Society depends on the surplus energy provided from the energy extraction sector for the material and energy throughput that allows for economic growth and productivity (Cleveland et al., 1984). As energy becomes more expensive to extract and produce, more money and energy that might otherwise be spent in other sectors of the economy must be spent in the energy sector, decreasing real growth (Hall and Klitgaard, 2012; Tverberg, 2012). Governmental subsidies play a considerable role in favoring existing fossil fuel energy resources over potential alternatives (Environmental Law Institute, 2009). Meanwhile the existing PV systems tend to have a very low EROI although the output tends to be higher quality

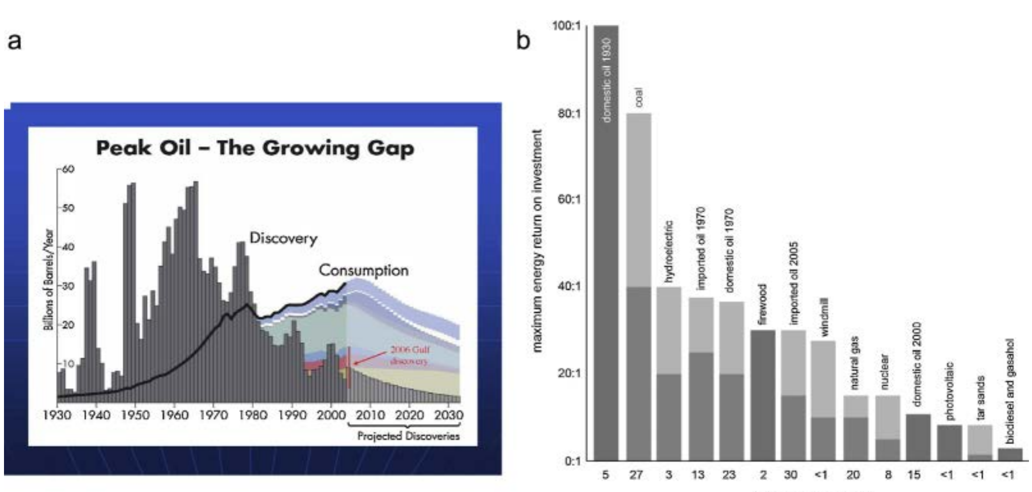

Fig. 2. (a) Worldwide oil discovery and consumption from 1930 to the present and project future discoveries (ASPO, 2008, used by permission). (b) Energy return on investment (EROI) of different energy sources (from Hall and Day, 2009, reprinted by permission of American Scientist, magazine of Sigma Xi, The Scientific Research Society). The 1930 oil figure is for discoveries. The other values are for production.

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electricity (Prieto and Hall, 2012; Palmer, 2013). The transition to a less oil reliant, more sustainable society in the U.S. is many decades away (Hirsch et al., 2010).

Since so much of the economy depends upon the widespread availability of cheap oil for the production and distribution of goods, the onset of peak oil and the decline in net energy available to society has profound implications for overall societal well being (Hall and Day, 2009; Hall et al., 2009; Murphy and Hall, 2011). Just as the first half of the oil age consisted of constantly increasing production, the second half of the oil age will consist of a continual rate of depletion that cannot be offset by new discoveries or low EROI alternatives (Hall and Pascualli, 2012). This will cause price rises that accompany increases in demand (IMF, 2012). There is no substitute fuel source for conventional oil that is as plentiful, has as high an EROI, and can be scaled up in time to meet demand. As a result, rising oil prices will effectively inhibit the type of economic growth (i.e. perpetually increasing material and energy throughput) experienced by countries such as the U.S. during the first half of the oil age.

Increasing scarcity and cost of energy will affect all of society but those cities and regions that can become less reliant on oil and other fossil fuels will be better off in the second half of the oil age. For example, cities with electrified mass transit and multi-modal commuter transit options are better prepared than those with uni-modal, automobile dependent transit. Cities that rely heavily on oil for the import of goods and services across long distances will be affected disproportionately than cities located in areas that have less of a dependence on imports and can live, at least partially, off of the surplus production provided by rich local ecosystems.

In conclusion, energy scarcity will impact all areas of the country and all sectors of the economy. However, it will combine with other megatrends, especially climate change, to make some regions, such as the Southwest, highly unsustainable. In the next section, we will show that resource-rich regions will be relatively less susceptible because ecosystem services can be tapped to soften the blow of increasing energy prices.

4. Ecosystem services

Ecosystem services (ES) are the ecological characteristics, functions, and processes that contribute to human well-being, either directly or indirectly, i.e. the benefits people derive from properly functioning ecosystems (Costanza et al., 1997; MEA, 2005). Ecosystem processes and functions may contribute to ES but they are not synonymous. Ecosystem processes and functions describe biophysical patterns and relations and exist regardless of whether or not humans benefit (Boyd and Banzhaf, 2007; Granek et al., 2010). Two examples are soil formation and protection of human infrastructure from storms by wetlands (Costanza et al., 2008).

The ecosystems that provide the services are referred to as “natural capital,” using the general definition of capital as a stock that yields a flow of services over time (Costanza and Daly, 1992). In order for these benefits to be realized, natural capital (which does not require human activity to build or maintain) must be combined with other forms of capital that do require human action to build and maintain. These include: (1) built or manufactured capital (buildings, highways, trucks, levees); (2) human capital (properly educated people); and (3) social or cultural capital (social networks and belief systems) (Costanza et al., 1997). These four general types of capital are all required in complex combinations to produce any and all human benefits.

ES thus refer to the relative contribution of natural capital (with other forms of capital) to the production of various human benefits. There are four general types of ES (MEA, 2005). These include provisioning services (such as production of fish and timber), regulating services (flood control, storm protection, and climate regulation), cultural services (recreation, aesthetic, and scientific benefits), and supporting services (soil formation, primary productivity, and habitat).

The human economy cannot exist without the ES provided by nature (Costanza et al., 1997). But these services are threatened by human activities such as extraction of resources from the environment, waste production and dumping, and the degradation of natural ecosystems (Rooney et al., 2012). Resource extraction can have negative impacts on ecosystem functioning directly when extraction rates are higher than replacement rates. Direct drivers of change in ecosystems also include land use change and the accompanying destruction of habitat, invasive species proliferation, and climate change. For example, changes in land use such as the movement towards biofuel production in an attempt to alleviate dependence on fossil fuels, leads to a product that not only contains little net energy (Farrell et al., 2006a; Farrell et al., 2006b; Murphy and Hall, 2011) but also perpetuates the degradation of ecosystem services at the landscape scale (Gomiero et al., 2010; Sheppard et al., 2011).

4.1. Spatial distribution of ecosystem services

ES in the U.S. are generally higher in the eastern states due to the higher amounts of rainfall and higher rates of primary production (Fig. 3). River valleys and coastal areas have particularly high levels of ES. Estimated monetary values range from $22,000/ha/yr for estuaries and $19,500/ha/yr for swamps and floodplains, to $8498/ha/yr for lakes and rivers, to less than $100/ha/yr for deserts and mountains (Costanza et al., 1997). However, mountains do intercept precipitation, store it as snow, and release it slowly over the year. The Mississippi alluvial valley and delta, in their natural state, were especially important in terms of ES in the U.S. The value of ES into the future will depend on how society manages these valuable ecosystems (Day et al., 2009).

Water and temperature are the two main drivers of primary productivity. Warmer, moist climates tend to have higher primary productivity and generally more ecosystem services than colder climates. Areas with high ES are often closer to the primary means of economic production (or provisional ecosystem services) such as fishing, agriculture, and forestry, with the exception of the mining sector that reflect ancient concentrations of minerals and fossil fuels. This is obvious from the global and national maps of natural biotic production (Fig. 3). Where populations are high in areas with less biotic productivity, i.e. areas with low ES, there must be a high subsidy with fossil fuels in order to produce resources at anywhere near the naturally occurring rates of environments with high ecosystem services. Examples of these subsidies include fuels used for large-scale water extraction from the Ogallala and Central Valley aquifers for irrigation, the extensive water management system in the Southwest, and the use of natural gas based fertilizers to produce food in low nutrient soils (Sophocleous, 2012; Scanlon et al., 2012). These subsidies allow the production of resources at a much larger scale and cheaper price than would otherwise be the case from these unsubsidized ecosystems.

4.2. Ecosystem services and the economy

As conventional oil availability continues to decline and its price rises, ES will become a more important factor in maintaining the human economy (Day et al., 2009). The modern industrial and agricultural revolutions have been subsidized with cheap energy. The transportation network and delivery of goods to low ES areas is also dependent on cheap energy. Sustaining natural systems and

Fig. 3. Spatial distribution of terrestrial net primary productivity (modified from U.S. EPA (2013)). The areas enclosed in dotted lines are megaregions shown in Fig. 5a. Circles indicate population of individual cities.

their ES will be much more difficult as the age of cheap energy ends (Fisher et al., 2011). People in those areas that either do not have rich, healthy ecosystems, or have greatly degraded ecosystems, will be increasingly dependent on resource imports or be forced to abandon the unsustainable landscape they inhabit. This increased dependency on resource exporting areas may become strained by increasing consumption of growing populations in those areas along with rising energy costs and climate change impacts (Foucher and Brown, 2007; Lordos, 2010). As ES decline, reliance on resource imports increases, and the sustainability of the system becomes more vulnerable to disturbance while becoming increasingly dependent upon expensive outside energy and material subsidies.

4.3. Ecosystem services and cities

Increasing concentrations of people in cities concentrates both demand for resources and the resulting wastes from consumption. Wastewater from urban areas and nutrient runoff from agricultural areas often degrade the biogeochemical processing capacities of aquatic ecosystems in downstream areas. Freshwater aquifer depletion arises from the unsustainable drawdown of water resources, especially in arid environments. Maintaining water supplies in water scarce areas often requires water imports from other areas, resulting in ecosystem degradation in these source areas. Alleviating water shortage becomes more expensive as the costs of pumping and maintaining water supply systems increase. As is the case with continued development of fossil fuel reserves, the best first principle applies as the most easy to access water resources are exploited first, and the harder to access resources are exploited last. Cities such as Los Angeles and Las Vegas provide textbook cases of such trends.

As declines in the energy and mining sector continue, the primary sectors of the economy based on ecosystem services provided by agriculture, fishing, and forestry will become more important to meeting the basic needs of populations, including for jobs. This suggests that the regions most threatened by the end of cheap energy, as well as climate change, will be those areas with low ecosystem services such as the Southwest and the southern Great Plains.

5. The Human economy: Neoclassical vs. biophysical

For the last century, and especially the last 50 years, the reigning economic paradigm has been neoclassical economics (NCE). But the utility of neoclassical economics (NCE), especially as related to natural systems, is declining as human society transitions from an empty to a full world (Daly, 2005). NCE is inadequate when it comes to valuing finite, absolutely scarce, non-substitutable resources in the economy. In addition, pollution and the degradative ecosystem impacts accompanying resource production and consumption, are externalities that are not generally accounted for in neoclassical economic models. Most advocates of indefinite economic growth view the environment as a subsystem of the economy when in fact the economy is a subsystem of the environment and is subject to the same biophysical laws that govern the planet (Daly, 2005; Day et al., 2009). More succinctly, the idea that infinite growth on a finite planet can occur indefinitely is a fallacy. In contrast, many ecologists and systems scientists have described system functioning as a resource limited process rather than a technology limited process (Hall and Klitgaard, 2012). The false perspective provided by the limitless growth, neoclassical economic viewpoint has contributed to misperceptions of how economies function. In this section, we briefly describe the major sectors of the economy and show that NCE is inadequate in addressing the problems occurring in a world where energy and other resources are becoming scarcer. The inability of NCE to address the problems resulting from energy scarcity, climate change, and declining ecosystem services suggests the need for alternative economic thinking such as biophysical economics (BPE) to mitigate against the impacts on the human economy of 21st century megatrends.

5.1. Major sectors of the economy

The economy is usually divided into four major sectors: primary, secondary, tertiary, and quaternary (Clark, 1957; Kenessey, 1987). The primary sector provides the raw materials and energy that underlie and sustain the rest of the economy (Fig. 4). This includes most non-renewables that are acquired through mining, while the other three subsectors, agriculture, forestry, and fisheries, come from harvesting renewable resources such as crops, timber, and seafood. The secondary, or industrial sector, includes industrial operations that produce finished products from raw materials through manufacturing, processing and construction, such as petroleum refineries and steel plants. The tertiary sector is composed of transportation, gas, electric, and sanitary services, along with wholesale and retail trade and human services including restaurants, healthcare, banking, and law. The quaternary sector includes the finance, insurance, and real estate sectors along with information technology, and public administration. The information technology subsector, which is dominated by intellectual activities including education and scientific research, provides important feedback to enhance the primary, secondary, and tertiary sectors. This feedback allows for an increase in efficiency and productivity in the overall economy. It is important to understand, however, that the primary sector is the foundation upon which all other sectors are based. Without the energy and products produced by the primary sector from natural resources, or access to these resources via trade agreements, the other sectors would cease to function. This point is fundamental to understanding the importance and relevance of increasing population, energy scarcity, climate change, and their impacts on ecosystem services in relation to the human economy.

In addition, it must also be recognized that economies must have fully functional primary and secondary sectors supplying products to the consumer based tertiary and quaternary sectors. For example, although the U.S. no longer has as large of a secondary sector economy as it did a century ago, the products produced in that sector are still available. Manufactured goods are provided by manufacturing intensive economies such as China. The consumers that exist in the upper level human service and technology economic sectors have demands that must be met by the primary and secondary level sector producers somewhere, if not domestically, then internationally. The longer supply chains established in such a global economy require large amounts of energy to maintain. The

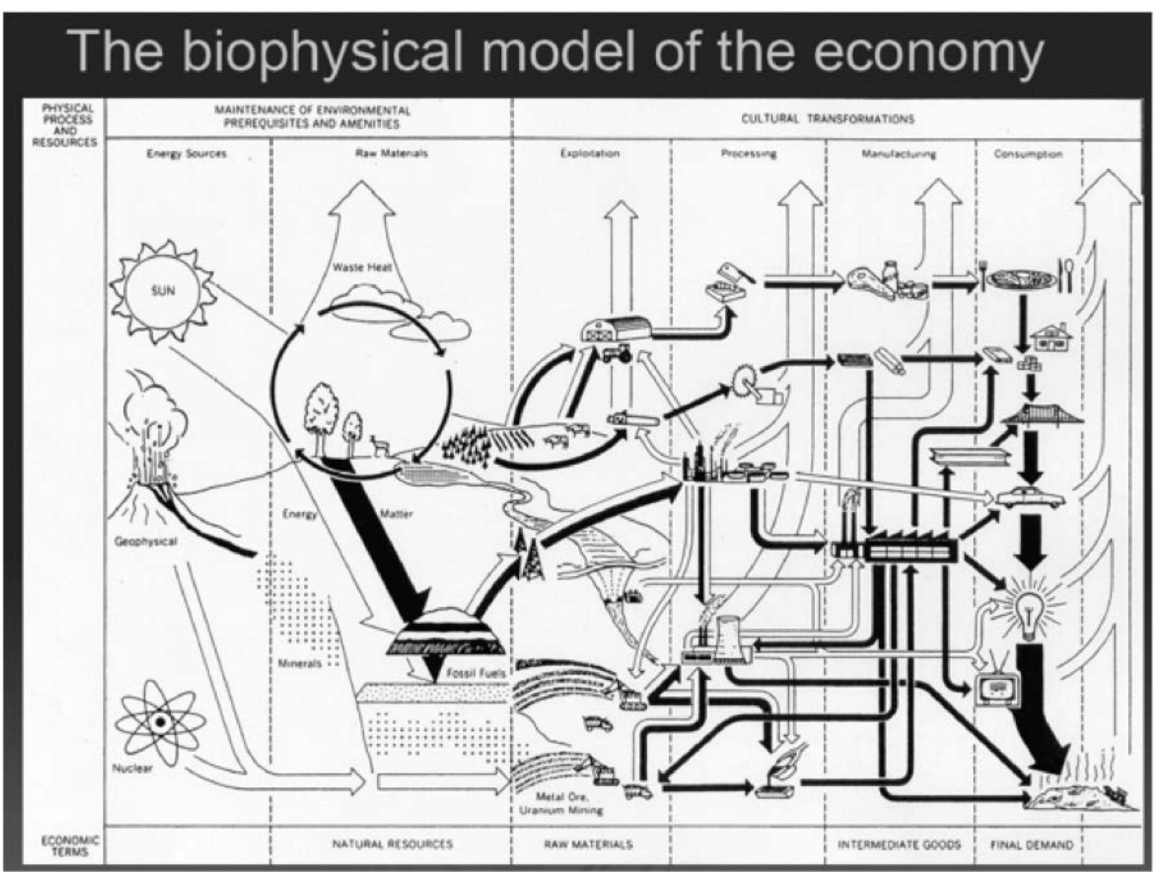

Fig. 4. Biophysical economy showing that the economy is ultimately dependent on flows of material and energy from the biosphere. Natural energies drive geological, biological, and chemical cycles that produce natural resources and public service functions. Extractive sectors use economic energies to exploit natural resources and convert them to raw materials, which are used by manufacturing and other intermediate sectors to produce final goods and services. These goods and services are distributed by the commercial sector to final demand. Non recycled materials and waste heat are returned to the environment as waste. (from Hall et al. (1986), used by permission).

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interdependence established by such an economy means that disturbance in one region or sector can have system level impacts. For example, the shift in corn production to meet increased ethanol demand can lead to rising corn prices on the international market thereby increasing the number of people who go hungry who then begin to protest such price increases which destabilizes the public sector within the disturbed state (e.g. Mexico tortilla riots 2007). Disturbance to economic systems can occur due to perturbations in the biosphere (i.e. drought, flood, severe weather events) and manifest themselves in the secondary, tertiary, and quaternary sectors. These events demonstrate the fact that important national and international events of our time are closely related to economic sectorial-structural adjustments that affect, and are affected by, natural systems.

5.2. The neoclassical description of the economy

Neoclassical economics (NCE) is the primary conceptual framework by which the human economy has been understood and managed for at least the past century. It is the dominant mainstream economic paradigm in the U.S. and the world today and has become the system whereby economic priorities of the state are determined and justified primarily by private market forces. NCE is characterized by the marginal utility theory of value, the mathematically stated general equilibrium model, and more recently various assumptions and pronouncements asserting that individualism and reliance on free markets as the best means for allocating resources and encouraging economic growth—while downplaying the role of government (Daly and Farley, 2004) and hardly mentioning natural ecosystems and their resources.

NCE was developed during a time of cheap energy and material availability. NCE has traditionally been a struggle between the ideas of the early 20th century economists John Maynard Keynes and Friedrich August von Hayek (Yergin and Stanislaw, 1998). Their ideas were being developed when the oil and gas resources of North America were just beginning to be developed and the reserves of countries throughout the world, especially in the Middle East, appeared limitless. The shift away from Keynesian state policy driven economics to von Hayek market driven forces largely occurred in the late 1970s (Blyth, 2013), after the peak in U.S. oil production. At the time, oil remained abundant and cheap, and to this day, oil provides an essential energy source to fuel the modern global economy. Because our understanding of peak oil, global climate change or the importance of properly functioning ecosystems did not mature until the 1980s or later, inputs from the biosphere did not contribute in any important way to the development of NCE theory (Daly and Farley, 2004; Hansen et al., 1988). But in fact it was only the increasing availability of fossil fuels (coal, oil, natural gas) that has enabled the most dramatic increase in population and economic growth in the history of the human species and the apparent effectiveness of market economics (Catton, 1982, see also Section 7). Increasing energy availability and the widespread adoption of fossil fuel dependent technology allowed the development of the modern consumer economy and a rapid increase in the production of material goods for global trade. Since WWII, the U.S. and most other nations have instituted policies that have pursued economic growth as the primary objective of their economy. Globalization has been one primary result. It is an extension of the increased drive for wider markets and increased profits at the cheapest cost to the producer (Chomsky, 1999). The conceptual framework within which NCE operates has become almost completely detached from biophysical reality but as energy and resources become scarce, the flaws and limitations of NCE are becoming more evident (Hall et al., 2001; Gowdy et al., 2010).

NCE disregards the relations between resource stocks and flows, and, in effect, considers all resources as endless flows. It treats the depletion of non-renewable resource stocks as current income and externalizes the cost of pollution (Gowdy et al., 2010). This was reasonable when natural resources and the ability of the biosphere to assimilate societal wastes were essentially unlimited. But current income comes at the expense of future generations who clearly will not have access to the non-renewable resource stocks being depleted, especially fossil fuels, but that will have to deal with the pollution created by industrial society. However, according to NCE assumptions, since natural capital can be substituted with human or man-made capital, the depletion of fossil fuels, fisheries, and forests should be of little concern. This concept of interchangeability of capital creates a sort of perpetual impunity regarding the consequences and reality of economic activity (Gowdy et al., 2010). Clearly this is at odds with how natural systems or the real economy function.

One of the major critiques of neoclassical economics is that it reduces the complexity of real production processes to capital alone. According to this viewpoint, human capital, manmade capital, and natural capital are absolute substitutes for one another (Gowdy et al., 2010). In essence, the idea of absolute substitution is based on the false notion of presumed unlimited capital (Gowdy, 2000). This misinformed assumption perpetuates the fallacy of infinite growth on a planet of finite resources. But it seems that most economists believe that technological progress is an all powerful process that will replace resources with ideas indefinitely.

A major problem with the neoclassical assumption of substitutability is that the market creates "the illusion of decreasing scarcity" (Georgescu-Roegen, 1972; Reynolds, 2002; Cobb, 2008). In short, the market does not reflect accurately the non-renewable resources due to a lack of complete information regarding total recoverable resource reserves and technology that confuses resource abundance with increased extraction efficacy often leading to faster depletion rates, lower efficiency in resource extraction and increasing scarcity. The amount of energy and time required for the transition to the "new energy future" are therefore unknowns. And it is questionable that such a techno-utopian future can exist without relatively inexpensive fossil fuels (Huesemann and Huesemann, 2011). Unless scarcity is properly represented in the market, price shocks will continue to occur that make the transition more expensive and difficult.

NCE focuses not on the resources that are the basis of real wealth but rather on problems related to value decisions, the behavior of economic actors, and the working of markets (Hall and Klitgaard, 2012). As such it is, and calls itself, a social science, not a natural or biophysical science. Yet clearly, modes of production must be addressed before any distribution of wealth can occur. The wealth distributed in the markets must be produced from raw materials in the environment that are subject to biophysical laws (Hall et al., 2001). And the environment must receive the waste products of economic activity. When the economy was small compared to the biosphere, these source-sink issues were not a problem. But now, humans are impacting the earth at a global level in many ways. Climate change is perhaps the best example of this. Unfortunately, mainstream NCE widely ignores these processes and their limits (Georgescu-Roegen, 1971; Daly, 1973, 1977; Leontief, 1982; Kummel et al., 1985; Hall and Klitgaard 2012) and thus is at odds with how natural systems function. In natural systems, when exponential growth occurs, it is short lived. Scarcity is pervasive in natural systems and is central to the idea of limitations to growth (e.g. Leibig's law of the minimum, limiting nutrients) and infinite substitutability does not occur (e.g. the Redfield ratio where specific elements are required in rather fixed ratios). In essence, the tenants of NCE worked as long as the source and sink functions of the biosphere were large compared to human activity, but this is not the case anymore.

5.3. Energy and the economy

The size and functioning of the economy is strongly related to energy consumption. Neoclassical, growth-based economies are measured by gross domestic product (GDP) that is related directly to energy use in the economy (Brown et al., 2011). Increasing energy and material throughput increases GDP and the U.S. economy entered into a recession each time the cost of oil increased to over 5% of GDP spending and total energy costs exceed 10% of GDP (Hall and Klitgaard, 2012). Increases in the price of oil and total energy relative to GDP decreases the amount of discretionary income consumers have to spend (Hamilton, 2009; Hall and Klitgaard, 2012). Declines in discretionary spending result in decreased consumption, thereby weakening an economy geared toward growth. The 2007–2008 oil price shock led to declines in consumer sentiment, manufacturing, and the automotive sectors, after oil price shocks had a multiplier effect leading to a decline in aggregate income and a loss in purchasing power over and above that caused by the initial price increase itself (Hamilton, 2009).

Much of the economy is based on spending discretionary income, and cities and regions whose economies are based heavily on spending discretionary income will be more affected by decreases in discretionary income as energy prices rise. Tourism based economies are highly vulnerable in this respect as fewer travelers spend fewer dollars in cities such as Las Vegas and Orlando and many others throughout the landscape. Some of the most dramatic declines in housing price values since the 2007 mortgage crisis also occurred in these two markets. Estimates made by Hamilton (2008) imply that a 1% reduction in GDP translates into a 2.6% reduction in demand for new homes. However, this decline in demand will not be the same across the country. For example, housing prices near the urban core of many cities saw home prices rise during the worst part of the mortgage crisis while homes on the outskirts with greater commuting distances declined in price and the number of foreclosures in these neighborhoods increased (Cortright, 2008). Thus, energy use is extremely important in maintaining the current growth oriented economy and the increasing cost and scarcity of energy will have a strong impact on the economy.

5.4. The biophysical underpinnings of the economy

Biophysical economics (BPE) is based on the assumption that the human economic system is grounded in the biophysical reality of the Earth. The natural laws of the behavioral sciences, biology, physics, and thermodynamics play an integral role in limiting the human economy and economic behavior. BPE is based on a conceptual model of the economy nested within, and sustained by, flows of energy, materials, and ecosystem services from the natural world (Cleveland et al., 1984; Hall and Klitgaard, 2006; Brown et al., 2011; Burger et al., 2012). Maintaining these flows into the human economy is threatened not only by declining fossil energy supply but also by the impacts of a changing climate and human impacts on the ecosystems that function to provide energy and materials to human society. The policymaking necessary to accomplish reductions to such pollution are difficult in the face of vested interests whose financial bottom lines depend on preventing adaptation to the new understanding of how the world operates and the requirements of transition towards a more sustainable future.

Biophysical and ecological economics demonstrate that the economy is a subsystem of the earth's ecosphere sustained by flows from the biosphere (Daly and Farley, 2004; Hall and Klitgaard, 2012). Ecological economics attempts to value ecosystem services accurately that are treated as externalities by neoclassical economics. These "externalities" are important because natural systems provide "free" goods and services to humans that are dependent on continued ecosystem function (i.e. wetlands, forests, fisheries, etc.) (Costanza et al., 1997; Lant et al., 2008). Many of these services are public goods that cannot be adequately managed by the present economic or political systems (Daly and Farley, 2004). The degradation of such services comes at a cost to future production beyond the scope of short-term markets. Ecological economics too often focuses on only including nature into the dominant NCE model that focuses on human willingness to pay (Hall and Klitgaard, 2006). In a sense, the environment is made conceptually a subset of the larger economic system. In contrast, biophysical economics recognizes the importance of ecosystem services without necessarily giving it a monetary value that is dependent on the value of currencies defined in the larger human society, while attempting to broaden the debate regarding the fact that invaluable economies exist everywhere in nature (Vermeij, 2004) and are subject to the same biophysical laws. BPE focuses on the energy requirements and entropy limitations that form the basis for modern economic systems. Unlike NCE, both biophysical and ecological economics recognize the concept of uneconomic growth (Daly, 1999), which is what occurs when the marginal costs of further growth outweigh the marginal benefits of that growth. In other words, at some point the costs to society of continued production outweigh the benefits of this production. Examples include the production of negative net energy resources, DDT, leaded gasoline, CFC's, and greenhouse gases. Because the flows of energy and materials from the environment to support the economy are not distributed evenly over the landscape, a fundamental conclusion of biophysical economics is that areas with higher natural flows of energy and materials will be more sustainable. Also, as energy supplies decline, the economy will shrink and areas with low natural resource productivity will be less sustainable.

6. Agriculture and food

The globalized industrial agriculture system is very energy intensive. A significant portion of food produced in the U.S. is irrigated and located in areas where water shortages will increase. Below we describe the food system and the potential impact of 21st century megatrends.

6.1. The current U.S. food production system

The American food supply system uses large areas of land and large quantities of water and is very energy intensive. Each American requires approximately 2000 L/year in oil equivalents to supply their food, which accounts for about 19% of the total energy use in the U.S.—Agricultural production, plus food processing and packaging consumes 14%, while transportation and preparation use 5% (Pimentel et al., 2008). About one-third of the energy required to produce a hectare of crops is invested in machine operation (Pimentel and Patzek, 2005). Mechanization decreases labor significantly, but does not contribute significantly to increased crop yields per acre. On average, nearly 10 calories of energy are invested to produce a calorie of edible food (Pimentel et al., 2008; Aleklett, 2012; Hamilton et al., 2013).

Cropland provides 99.7% of the global human food supply (measured in calories) with less than 1% coming from the sea (FAOSTAT, 2004). At present, global per capita agricultural land is 0.22 ha for cropland and 0.5 ha for pastureland (Pimentel and Pimentel, 2008). However, the U.S. and Europe use 0.5 ha of cropland and 0.8 ha of pasture per capita to support their diverse and protein-intensive food systems (Pimentel and Wilson, 2004; USDA, 2004). Cropland now occupies 17% of the total land area in the U.S., but little additional land is available or even suitable for future agricultural expansion (USDA, 2004). As the U.S. population increases, climate impacts grow, and energy resources decrease, there will be less cropland area per capita. Presently, the Chinese, who live primarily as vegetarians and import large quantities of grain to supplement their diets, have only 0.08 ha of cropland per person, a much lower value than that projected for the U.S. even in 100 years (Pimentel and Wen, 2004).

There were 943 million acres of agricultural land in the U.S. in 2000, down from 1.25 billion acres in 1950 (a 21.5% decrease, USDA, 2013b). This land is not equally distributed across the country but occurs in several different major agricultural regions. The Midwest corn and soybean belt that includes the states of Ohio, Indiana, Illinois, Wisconsin, Minnesota, Iowa and Missouri has 135.7 million acres. The plains states and southwest including the states of North and South Dakota, Nebraska, Kansas, Oklahoma, Texas, New Mexico, Colorado, Montana, and Wyoming have 508 million acres. California has 27.8 million acres. The remaining 172 million acres are mainly in the east. California's 27.8 million acres produces about 50% of the vegetables, fruits, and nuts of the country. The corn-soybean belt is an extremely productive bread basket region. The Great Plains produces wheat and cattle, but much of the area is low intensity farming and grazing.

Crops require large amounts of water for photosynthesis, growth, and reproduction (Pimentel et al., 2004). Various crops use water at rates between 1000 L and 2000 L of water per kg dry matter of crops produced. The water required for corn per hectare is about 10 million L. Even with an annual rainfall of 1000 mm in the U.S. Corn Belt, corn frequently suffers from insufficient water during the critical summer growing period (Pimentel et al., 2004). A hectare of high-yielding rice requires approximately 14 million L/ha for an average yield of 7 metric tons (t) per ha (Pimentel et al., 2004). On average, soybeans require about 6 million L/ha for a yield of 3.0 t/ha. In contrast, wheat, which produces less plant biomass than either corn or rice, requires only about 2.4 million L/ha for a yield of 2.7 t/ha. Under semiarid conditions, yields of non-irrigated crops, such as corn, are low (1.0 t/ha to 2.5 t/ha) even when ample amounts of fertilizer are applied (Pimentel et al., 2004). Irrigated land per capita in the U.S. has remained constant at about 0.08 ha (USDA, 2003). Approximately 40% of water use in the United States is used solely for irrigation (USGS, 2003). Reducing irrigation dependence in the U.S. would save significant amounts of energy, but probably require that crop production shift from the dry and arid western regions to the more agriculturally suitable eastern U.S.

6.2. Impacts of mega trends on agriculture

Agriculture will be impacted by water shortages and increasingly depleted ground water and projected climate change and energy costs for fertilizers, pumping water from deeper depths in major aquifers, and generally energy intensive modern agriculture. We are not aware of any integrated study about the future costs of agricultural production given the megatrends of the 21st century. Clearly this is a very important issue that needs much more careful study. As a general rule of thumb, most agriculture in the arid west is not possible without irrigation. This is significant since the southern Great Plains produces much of the beef in the U.S., and 50% of vegetables, fruits, and nuts are produced in the Central and Imperial valleys of California. The Central Valley averages about 10 in. of rain per year while the Imperial Valley averages less than 5 in. Reservoirs in much of the Southwest have been below capacity for many years. Increasing temperatures, lower rainfall, and high demand point to chronic water shortages for decades to come (USDA, 2013a).

Several solutions have been proposed to deal with growing water shortages in the Southwest. One is to shift water from agriculture to urban and industrial uses. In California, almost 80% of water use is for agriculture (Hanak et al., 2011) which is similar to other western states, and some economists argue that the value added per unit of water use is much less in agriculture than in other uses (Reisner, 1993). One "simple" solution to the water shortage is to stop farming on some or most of the current irrigated farmland. But how much of this agricultural land is critical? Any significant reduction in farming would have serious implications for the nation's food supply and it is obvious that the competition between agriculture and other uses for water is a very complicated issue. And given projections for progressively worsening water shortages, shifting away from agriculture can only work for so long.

The Great Plains stretch from Texas to Canada and support wheat farming, cattle ranching, and assorted other agricultural activity. Much of the area is underlain by the Ogallala aquifer that extends over parts of eight states and experiences very little recharge. Vast amounts of water are pumped from the aquifer and without this water much of the agricultural richness of the Great Plains would not be possible (Ashworth, 2007). Precipitation is expected to decrease over much of the Great Plains due to climate change (USDA, 2013a,b). This will make the area even more dependent on irrigation water pumped from the Ogallala aquifer but water levels are falling across large areas of the Ogallala (Ashworth, 2007; USGS, 2003). As water levels decline energy costs for pumping increase.

Thus, agriculture will be impacted by climate change and the increasing cost of energy. Climate change will threaten production in much of the western U.S. as water becomes more scarce. Increasing energy costs will make industrial agriculture more costly. Agriculture may become more local and less productive during the 21st century but some areas may not be able to feed themselves from local production.

7. Settlement patterns and population distribution

Populations interact with the factors discussed above as they vary across the landscape to impact the sustainability of urban areas and regions. Historic population growth and settlement in the U.S., primarily from east to west, reflects a high natural rate of increase and high rates of immigration. This growth was fueled by exploitation of the immense natural capital of North America and then the increasing availability of cheap fossil fuels during the 20th century. U.S. population increased steadily from 3.9 million in 1790 to nearly 310 million in 2010. Life also became progressively more urbanized and by 2010, 259 million people or 83% lived in urban areas compared to 56 million in rural areas (U.S. Census Bureau, 2012).

Settlement patterns were also influenced by the economic opportunities available in regions during different time periods. Transportation technology and climate control of the built environment, both very energy intensive, influenced settlement patterns, especially in the second half of the 20th century. Domestic resource constraints to maintain population were offset by resource imports from abroad. During the 21st century, the end of cheap fossil fuels, climate impacts, and degraded ecosystems, will limit the ability of large urban areas and regions to function as they have for the past century. This problem will be much more acute in some parts of the country.

Historic settlement patterns in North America were traditionally based in areas of abundant natural resources and along trade routes, such as coastal areas and along rivers with fertile soils. Cheap energy underwrote the emergence of large cities detached from the constraints of local natural resource dependency and facilitated the development of non-water based transportation systems that played a role in the growth of cities in resource poor locales.

In 1800, most people lived on the east coast, with the exception of New Orleans. By 1850, two trends are evident; high growth rates in some cities and the spread of population away from the coast. By 1900, the industrial revolution was transforming society. All of the largest cities, however, continued to be located in rich natural environments. By the mid to late 20th century, this had changed. Some cities, such as Detroit, peaked in population and began to decline. These trends were associated with the growth of suburbs, construction of the interstate highway system, the westward shift of the population, and the increasing affluence that allowed people to live where they preferred due to climate control technology. The G.I. bill after World War II allowed veterans to purchase houses in the suburbs with low interest loans leading to widespread suburbanization. By 2000, major changes had taken place in population distribution. More than half of the largest cities were west of the Mississippi, most in arid areas where large cities could not exist without cheap energy.

7.1. Population distribution

Current population distribution in the U.S. is dominated by 11 megaregions (Fig. 5a). The densest megaregion, the Northeast stretching from south of Washington to north of Boston, is projected to increase from more than 49 million people in 2000 to nearly 60 million in 2025. The Great Lakes megaregion encompasses the major urban centers of the Midwest including Chicago, St. Louis, Detroit and Cleveland and is expected to contain over 62 million inhabitants by 2025. Sunbelt regions in Florida, Arizona, and southern California grew rapidly in the second half of the 20th century. The Texas triangle megaregion was fueled by the energy sector based economy of Houston and Dallas. Less populated megaregions exist along the Front Range of the Rocky Mountains near Denver and in Northern California around San Francisco Bay. The Cascadia megaregion includes Portland and Seattle, the Gulf Coast megaregion extends from southeast Texas to the Florida panhandle, and the Piedmont Atlantic megaregion includes Birmingham, Atlanta and parts of the Carolinas.

Today, many areas rich in natural resources and with economies based in the primary sector of the economy often have elevated poverty rates, perhaps due to what is commonly known as the resource curse, or the paradox of plenty (Freudenburg, 1992). The resource curse concept usually is applied internationally to countries that are rich in natural resources or minerals, (agriculture, forestry, fisheries, mining, and fossil fuels) but financially poor and stratified with regards to social class. However, we believe that this concept can also be applied to states. Fig. 5b shows that most underperforming counties are rural. These are regions that have not kept pace with national trends over the last three decades in terms of population, employment, and wages (Regional Plan Association, 2009). Note that with the exception of the Great Lakes megaregion, the underperforming regions are outside of the eleven megaregions. These underperforming areas generally have high natural resources and agricultural production.

Most expect the trend towards increased urbanization to continue throughout this century. But this depends on a smaller and smaller percentage of the population providing the basic resources (food, forest products, minerals, energy) that form the foundation of the economy that supports the many. This trend in the consolidation of industry and outsourcing is dependent on cheap energy that supports high-yield agriculture and the transportation of products across great distances. As energy prices rise, it is likely that diversified small-scale local production will become increasingly necessary. It is interesting to note that the only time since 1900 that the percentage of persons living in rural areas increased was during the great depression (U.S. Census Bureau, 1995; WSDOT, 2013a,b).

The maintenance of large urban megaregions requires enormous continuous inputs of energy and materials. Rees (2012) argues that modern industrial society and modern cities are inherently unsustainable. From an energetic standpoint, "cities are self-organizing far-from-equilibrium dissipative structures whose self-organization is utterly dependent on access to abundant energy and material resources." Cities are open systems that are dependent on the materially-closed biosphere. Modern first world cities especially are concentrated areas of material and energy consumption and waste generation that are dependent on large areas of productive ecosystems and waste sinks located far from cities. But human impact now is greater than the regenerative capacity of many, perhaps most, ecosystems. Some have argued that large urban areas are more energy efficient than rural areas (Dodman, 2009). But Fragkias et al. (2013) examined the relation between city size and greenhouse gas emissions and found that emissions scale proportionally with urban population size for U.S. cities and that larger cities are not more emissions efficient than smaller ones. In a review of energy and material flows through the world's 25 largest urban areas, Decker et al. (2000) also concluded that large urban areas are only weakly dependent on their local environment for energy and material inputs but are constrained by their local areas for supplying water and absorbing wastes. Rees (2012) contends that if cities are to be sustainable in the future, they must rebalance production and consumption, abandon growth, and relocalize. The trajectory of megatrends of the 21st century will make this difficult for all large urban regions in the U.S. and impossible for some. In the final section, we will address this point in more detail.

8. Synthesis

The megatrends described above will impact human and natural systems at the landscape level differentially (Fig. 6). Emerging energy scarcity will pervasively impact the economy making almost everything more expensive and reducing discretionary income. This will interact with climate change, ecosystem services and population density to differentially compromise the sustainability of different regions. Fig. 6 is a holistic, macroscopic depiction that is meant to show general patterns of compromised sustainability at a landscape level for the U.S. rather than a prediction for any specific point in the landscape.

Large urban areas are at risk due to the megatrends of the 21st century that we describe in this paper (climate change, energy scarcity, degradation of ecosystem services) because they have such high demands for continuous inputs of energy and materials as discussed by Rees (2012). By 2025, it is estimated that 165 million people, or about half the population, will live in four megaregions; the Northeast, Great Lakes, Southern California, and San Francisco Bay regions (see Fig. 5a). An additional 45 million will live in south Florida and the Houston-Dallas region. Large cities are often touted as more energy efficient than suburban or rural areas, but all megaregions have extensive suburban and exurban areas and city size is not related to greenhouse gas emissions (Fragkias et al., 2013). And the supply lines that support these megaregions with food, energy, and other materials stretch for long distances across the landscape. Areas dependent on longer, energy intensive

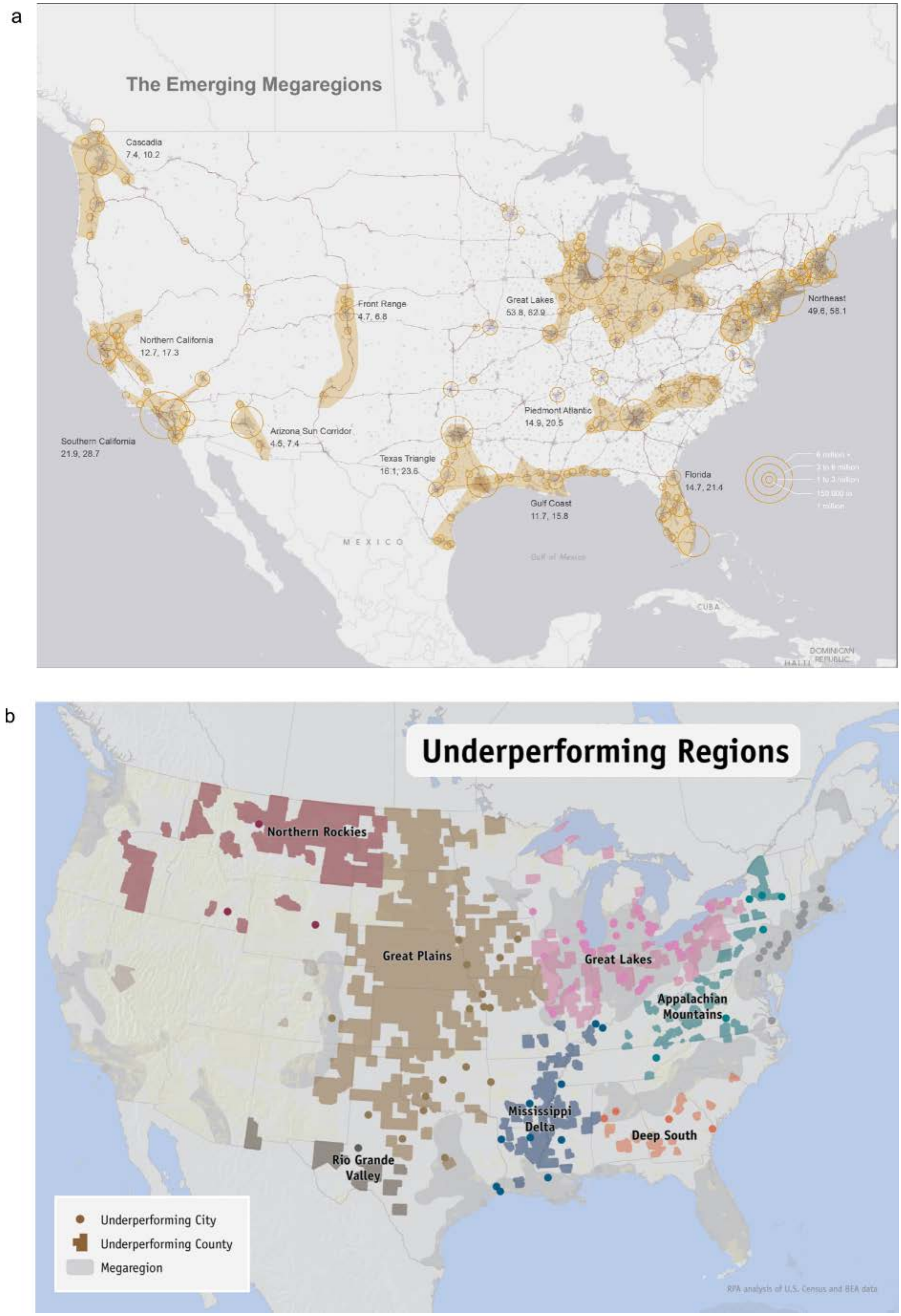
a
The Emerging Megaregions
Cascadia
7.4, 10.2
Northern California
12.7, 17.3
Southern California
21.9, 28.7
Arizona Sun Corridor
4.5, 7.4
Front Range
4.7, 6.8
Texas Triangle
16.1, 23.6
Great Lakes
53.8, 62.9
Piedmont Atlantic
14.9, 20.5
Gulf Coast
11.7, 15.8
Florida
14.7, 21.4
Northeast
49.6, 58.1
MEXICO
CUBA
b
Underperforming Regions
Northern Rockies
Great Plains
Great Lakes
Appalachian
Mountains
Mississippi
Delta
Deep South
Rio Grande
Valley
Underperforming City
Underperforming County
Megaregion

Fig. 5.

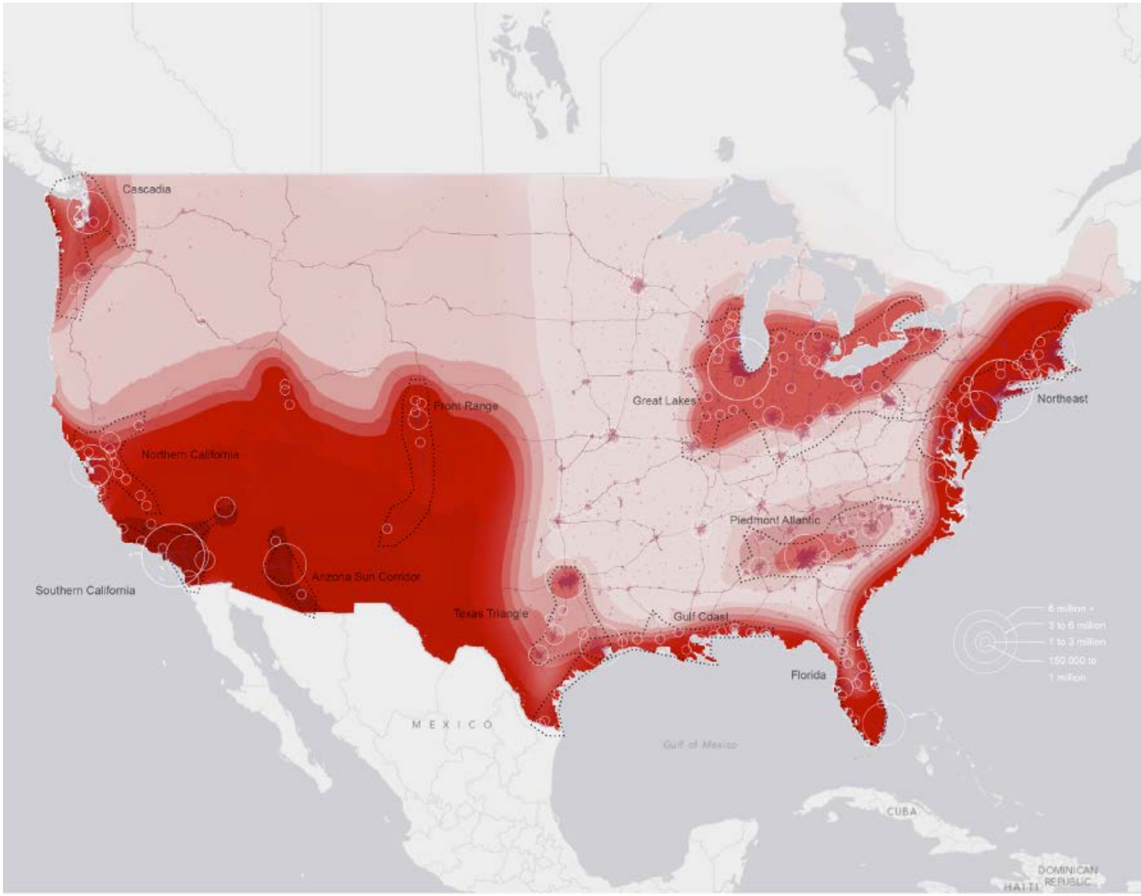

Fig. 6. Based on our analysis, several areas of the U.S. will have compromised sustainability in the 21st century. These include the southern Great Plains, the Southwest, the southern half of California, the Gulf and Atlantic coasts (especially southern Louisiana and Southern Florida, and areas of dense population such as south Florida and the Northeast. Although this map is for the U.S., the trends extend into Canada and Mexico. See text for discussion. The 11 megaregions from Fig. 5a are shown.

supply lines are vulnerable to the rising costs of energy for transportation.

The economies of urban areas, especially the currently most economically successful ones based on the human, financial, and information service sectors, are strongly dependent on the spending of discretionary income, which is predicted to decrease substantially over the 21st century (Hall and Klitgaard, 2012). But many cities have lost population, especially those that were based in the manufacturing sector of the economy during the 20th century. Detroit and Flint, Michigan, are often cited as examples but there are many others (Rappaport, 2003). Between 1950 and 2000, St. Louis lost 59% of its population. Pittsburgh, Buffalo, Detroit, and Cleveland lost more than 45% each. It is possible that many of the rust belt cities that have experienced population decreases will be more sustainable than more “successful” cities in the northeast and other areas. They now have a lower population density and tend to exist in rich agricultural regions. Indeed, abandoned land is being used for food production in a number of depopulating cities. By contrast, the northeast is the most densely populated region of the country. The population is expected to reach almost 60 million by 2025. The states that make up the region have about 34 million acres of farmland or about 0.2 ha per person. By contrast, it takes about 1.2 ha per capita to provide the food consumed in the U.S. (Pimentel et al., 2008). If agriculture becomes more local and less productive as some predict due to increasing energy costs (e.g. Rees, 2012), then it will be a challenge to maintain the current food supply to the northeast, especially at the price society is used to paying.

The least sustainable region will likely be the southwestern part of the country from the southern plains to California. Climate change is already impacting this region and it is projected to get hotter and drier. Winter precipitation is predicted to be more rain and less snow. These trends will lead to less water for direct human consumption and for agriculture. This is critical since practically all agriculture in the region is irrigated. The Southwest has the lowest level of ecosystem services of any region in the U.S. (Fig. 3). California is the most populous state in the nation with most people living in the southern half of the state, the area with

Fig. 5. (a) The eleven megaregions that contain most of the population of the U.S. The two numbers by each megaregion are the population, in millions, in 2000 and projected for 2025. (Used by permission, Regional Plan Association, America 2050 Initiative). (b) Underperforming counties are those that have not kept pace with national trends over last three decades in terms of population, employment, and wages. Data are from the Census and the Bureau of Economic Analysis related to population growth, employment growth, and wages for all of the more than 3000 counties in the nation from 1970 to 2006 (Source America 2050). An index was created based on four criteria to identify underperforming counties: (1) Population change from 1970–2006, (2) Employment change from 1970–2006, (3) Wage change 1970–2006, (4) Average wages in 2006. Counties that were ranked in the bottom third in at least three of these categories were considered underperforming. (Used by permission, Regional Plan Association, America 2050 Initiative).

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highest water stress. The Los Angeles metro area is the second largest in the nation. But population density is low over much of the rest of the region and is concentrated in large urban areas such as Las Vegas, Phoenix, and Albuquerque. California is one of the most important food producing states in the nation but this will be threatened by water scarcity and increasing energy costs. Much of the region is strongly dependent on tourism and spending discretionary income, especially Las Vegas, so future economic health will likely be compromised in coming decades. Many cities and regions whose economy is dependent on tourism will have compromised sustainability.

The Gulf and Atlantic coasts have high ecosystem services but are also highly vulnerable to climate change in terms of accelerated sea-level rise and more intense hurricanes. The southern parts of Florida and Louisiana have large areas near or below sea level that are threatened by climate change. Miami and New Orleans are highly vulnerable but all coastal cities have significant areas near sea level. Coastal areas have very high levels of ecosystem services that are also susceptible to climate change. Hurricanes Katrina, Irene, and Sandy are likely harbingers of the future of these coasts.

In summary, the emerging megatrends of the 21st century will result in large challenges for sustainability in the U.S. While it is difficult to predict this with a high level of precision, we believe that the most difficult areas to maintain are likely to be the southwest and especially southern California, coastal regions of the Gulf and Atlantic coasts, and large urban regions especially those in the northeast, southern Florida, and the southern half of California. Fig. 6 shows these areas of compromised sustainability. Additional study is needed to more carefully define sustainability of specific cities and regions, especially for those regions with lower compromised sustainability.

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