Landscape Ecol (2011) 26:755–773
DOI 10.1007/s10980-011-9606-2

PERSPECTIVE

The land use–climate change–energy nexus

**Virginia H. Dale · Rebecca A. Efroymson ·
Keith L. Kline**

Received: 18 October 2010 / Accepted: 11 April 2011 / Published online: 15 May 2011

Abstract Landscape ecology focuses on the spatial patterns and processes of ecological and human interactions. These patterns and processes are being altered by both changing resource-management practices of humans and changing climate conditions associated, in part, with increases in atmospheric concentrations of greenhouse gases. Dominant resource-extraction and land-management activities involve energy, and the use of fossil energy is one of the key drivers behind increasing greenhouse gas emissions as well as land-use changes. Alternative energy sources (such as wind, solar, nuclear, and bioenergy) are being explored to reduce greenhouse gas emission rates. Yet, energy production, including alternative-energy options, can have a wide range of effects on land productivity, surface cover, albedo, and other factors that affect carbon, water, and energy fluxes and, in turn, climate. Meanwhile, climate influences the potential output, relative efficiencies, and sustainability of alternative energy sources. Thus, land use, climate change, and energy choices are linked, and any comprehensive analysis in landscape ecology that considers one of these factors should be cognizant of these interactions. This analysis explores the implications of linkages between land use, climate hange, and energy and points out ecological patterns and processes that may be affected by their interactions.

Keywords Bioenergy · Climate change · Disturbances · Energy · Fossil fuel · Greenhouse gases · Landscape ecology · Solar energy · Wind energy

Introduction

For centuries, humans have modified terrestrial and aquatic systems to meet basic energy needs as well as to satisfy other requirements, leading to major changes in global land cover, atmospheric concentrations of greenhouse gases, and the land's future capacity to sequester carbon. Together, land use, energy use, and climate change represent three major, intertwined forces of human-induced global change. Numerous studies have examined influences of these forces, but our literature review failed to identify any

V. H. Dale (✉) · R. A. Efroymson
Center for Bioenergy Sustainability, Environmental
Sciences Division, Oak Ridge National Laboratory,
Bethel Valley Road, Building 1505, Room 200,
P.O. Box 2008, Oak Ridge, TN 37831-6036, USA
e-mail: dalevh@ornl.gov

R. A. Efroymson
e-mail: efroymsonra@ornl.gov

K. L. Kline
Center for Bioenergy Sustainability, Environmental
Sciences Division, Oak Ridge National Laboratory,
Bethel Valley Road, Building 2040, Room E233,
P.O. Box 2008, Oak Ridge, TN 37831-6301, USA
e-mail: klinekl@ornl.gov

analysis that considered their combined effects from a landscape-ecology perspective. This paper discusses major research issues within the land use–climate change–energy nexus that are best addressed from the point of view of landscape ecology and thus with a focus on patterns and processes.

Cumulatively, the ways in which people transform and use the land represent the most significant human modifications to our planet. The advent of agricultural cultivation allowed people to live in settlements, and the subsequent establishment of urban centers and transportation routes instigated major changes in patterns of land use (Scarre 2009). Human beliefs and conduct continue to affect the makeup and transformation of landscapes in an increasingly metropolitan world (Musacchio 2009). Although Forman (1995) has suggested that it would be ideal to design land-use practices from a broad-scale and landscape perspective, in actuality, modern land-use decisions are based on local economic, social, cultural, biophysical, political, and demographic forces within a spatial and temporal context (Geist and Lambin 2002; Lambin et al. 2003; Kline et al. 2009). Human occupation has direct effects on the land it occupies and has both direct and indirect down-slope, downstream, and downwind ecological effects dispersed across larger scales. For example, linear features, such as roads, oil and gas seismic exploration grids, transmission lines, drainage ditches, causeways, and dams, can both provide access to new areas and disrupt ecological functions of adjacent lands (e.g., Laurance et al. 2006). Such land-use changes, including historic deforestation, affect global atmospheric carbon dioxide (CO_2) concentrations, aerosols, and albedo and thus global climate. And equally important, management practices influence current and future carbon-carrying capacity and the flux of greenhouse gases between land and atmosphere, thereby qualifying the role of terrestrial ecosystems in mitigating climate change.

Climate change has been identified as an important threat to the persistence of our species on Earth and the most important challenge of our times (IPCC 2007). Earth's current atmosphere and climate are products of biotic activity that occurred over eons. Climate change that occurred 10,000 years ago as the Holocene period became warmer and wetter than the Pleistocene may have facilitated the domestication of plants and animals, ushering in a transition from relatively stable populations of nomadic hunters and gatherers, to a population explosion with impacts reflected by civilizations that dominate global landscapes today (Gupta 2004). While Earth's climate has fluctuated over millennia because of many factors, data support the scientific consensus that the current rapid global warming is unequivocally attributable to human activities (IPCC 2007). The recent rate of change in global annual average temperatures is unprecedented in the data record and is largely attributed to emissions of greenhouse gases caused by human activities. The rate of change in emissions has increased by 70% between 1970 and 2004, driven primarily by expanding fossil-fuel combustion (IPCC 2007). By 2008, CO_2 emissions from fossil fuels reached 8.7 Pg C per year, representing 88% of global anthropogenic CO_2 emissions and reaffirming fossil fuels as the most important and rapidly growing source of greenhouse gas on Earth (Le Quéré et al. 2009).

The implications of global climate change for humanity vary over space and time. Increases or decreases in temperature and/or precipitation are place-specific, and average temperatures and rainfall statistics can mask increases in the frequency, duration, and intensity of extreme events (such as droughts and floods), which appear to be on the rise in many areas and are strongly correlated with weather-related losses of life and welfare (NOAA 2010). Climate-change effects on ecosystems are expected to include species shifts (Root et al. 2003; Briones et al. 2009), increased risk of species extinction (Sinervo et al. 2010), phenology changes (MacMynowski and Root 2009), increased damage from storms and wildfires (Rosenzweig et al. 2008), and loss of coastal zones (IPCC 2007).

In addition to human-induced land-cover and climate changes, implications of energy technologies and uses must be considered as a third major factor in global change. The use of biomass for heating and cooking prevails as the primary source of energy for about half of humanity and a majority of the poor. Inefficient combustion and unsustainable resource management contribute to direct emissions, land-use changes, and deforestation dynamics, particularly around urban centers in developing nations. But per capita energy consumption in these nations is low compared to that of industrialized countries. The more developed nations of the world [e.g., the 34 countries that are members of the Organization for Economic Co-operation and Development (OECD) and those from the former Soviet Union] were responsible for more than half of global CO_2 emissions from all sources of energy in 2008, and China represented another 22% of the global total (IEA 2010). The same IEA report notes that China's share represented less than 6% of global emissions in 1973. As the rest of the people in the world strive to "catch up" with more developed nations, they account for an increasing share of new emissions. More than 70% of the growth in global greenhouse gases in 2004 was attributed to less-developed and developing nations (Raupach et al. 2007), but the per capita emissions in industrialized countries remained 10–20 times higher than per capita emission rates for less-developed countries (Baumert et al. 2005).

Energy sources and uses have become more diverse with time. With increasing global population and economic development, there has been a rising demand for energy from nuclear, hydro, wind, solar, ocean (tides, currents, waves, and thermal), and geothermal sources in addition to the well-established historic uses of fossil fuels, fuelwood, charcoal, residues, and dung. At the same time, new technologies are being developed for traditional fuels (for example converting coal or biomass to liquid fuels). Each type of energy use influences the environment throughout its life cycle via extraction of requisite raw materials, transport from the source to the production center to the end user, production processes and secondary wastes, end use, and final waste products. The life-cycle pathways also present different opportunity costs in terms of current or future benefits that are foregone because of today's choices. These supply-chain processes are spatially distributed in different patterns across the landscape. Thus, extraction, use, and disposal associated with each energy source and pathway affect the Earth's surface and systems in different ways. The availability and economic viability of energy choices are influenced by past land-use decisions and prevailing climate conditions. Likewise, these energy choices can, in turn, affect future land use and climate.

Human-induced changes in land use, climate, and energy must be viewed in light of the natural and ongoing changes on the Earth. Many natural disturbances are related to atmospheric cycles, ocean currents, plate tectonics, volcanoes, asteroids, and other planetary forces. At the same time, some very slow, ongoing climate changes can be explained by Milankovitch cycles (Hays et al. 1976). Global changes in disturbance regimes and climate are recorded in the geologic record. Ice-core data are now seen as a vital reference data set against which human-induced changes to the Earth can be interpreted (Ahn and Brook 2008). In a prior analysis of the interface between climate change and land use (Dale 1997), a key interaction that emerged is that humans adjust land-use practices to accommodate climate change and other forces and that these adaptations have ecological effects.

Furthermore, changes in land-use practices can affect the drivers of climate change. For example, large-scale clear-cutting of forests can have consequences for local weather patterns as well as greenhouse gas concentrations that influence climate (e.g., Sivakumar and Stefanski 2007). When vegetation is cleared and burned, carbon and soot from combustion are released to the atmosphere, and ecosystem carbon sequestration is reduced. Both changes contribute to increased atmospheric greenhouse gas concentrations in the short term. Furthermore, local transpiration is reduced, resulting in less cloud cover and higher surface temperatures. In turn, the reduced cloud formation decreases precipitation, drying the land and affecting future usage (Dickinson 1991). Reduced precipitation plus higher surface temperatures can increase the extent and intensity of fires and can lead over time to self-reinforcing cycles of forest loss and emissions, cycles that are further exacerbated if climate change instigates increasing frequency and intensity of drought and periods of abnormally high temperatures.

This paper explores how the focus of landscape ecology on patterns and processes can offer insights into the dynamic processes and interactions among climate change, energy choices, and land-use activities. It first explores influences by considering all possible pairings of climate change, land-use change, and energy use and then discusses the complications and benefits of examining all three factors at once (Fig. 1). The paper concludes by discussing research needs for landscape ecology related to the interfaces among land use, climate change, and energy. Decision makers need integrated approaches to consider the changes that policies can induce in climate, land use, and energy use and the resultant implications for the environment.

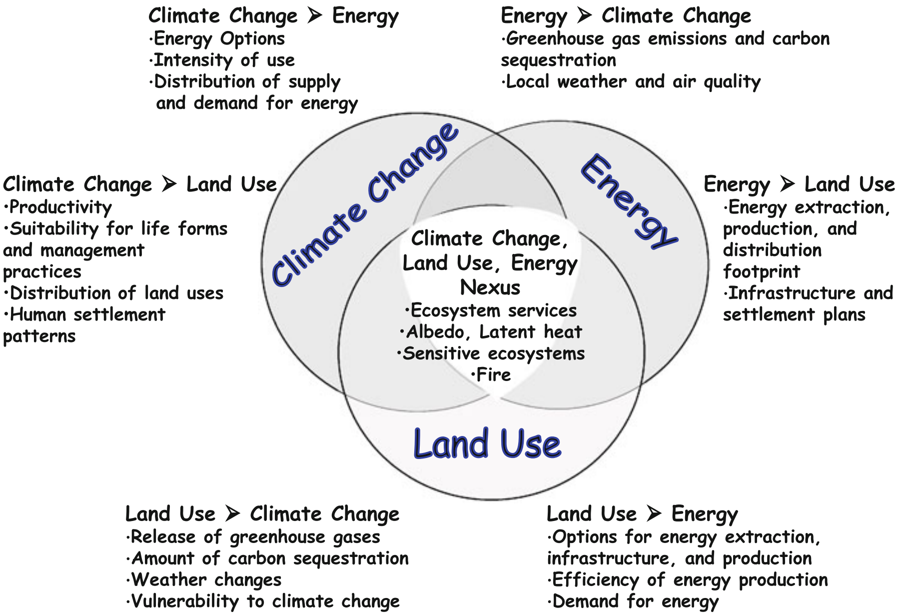

Fig. 1 Relationships among energy, land use, and climate change. Arrows indicate influence of one factor on another

Interactions among land-use change, climate change, and energy

Effects of energy on land use

Land-use patterns around the globe can often be traced back and linked to the availability and development of energy resources. Early civilizations flourished around abundant forest resources; and in more recent times, human settlements have expanded where there was sufficient wood for fuel and water for power (Perlin 1989). Settlements also followed development booms surrounding easily accessible fossil fuels and industries that emerged to extract, process, and transport energy supplies to users and markets. Where cheap, convenient energy is provided, people settle; towns spring up; and land uses change for the long term.

Land-use practices today continue to be affected by the energy life cycle, depending on the location of use or extraction and the travel distance to the next step in the supply chain or end use. Energy life cycles include materials exploration, extraction, production, refinement, distribution, and use. Energy development can impact land use in many ways, ranging from mountaintop removals and surface mining to the re-routing of rivers and flooding for hydroelectric dams. Infrastructure needed for energy production and distribution, such as railways, wells, roads, pipelines, refineries, and power grids, have directly influenced subsequent and neighboring land uses.

Pressures on the land for energy exploration and extraction continue, as exemplified by demands of oil and gas interests in the western Amazon, one of the last remaining forest frontiers. For example, in Ecuador, patterns of deforestation closely reflect road networks associated with oil exploration and development (Viña et al. 2004). And half (48.6%) of the Peruvian Amazon was recently offered for oil and gas concessions, bringing the total area affected by past and current fossil-fuel concessions to 84% of the region. New concessions will add to the past disturbances provoked by more than 100,000 km of seismic lines and 679 exploratory and production wells (Finer and Orta-Martinez 2010). In total, about 180 oil and gas development concessions in the western Amazon cover nearly 700,000 km^2 of critical remaining habitat for amphibians, birds, and mammals, according to studies by Finer et al. (2010).

Key characteristics of impacts of energy on land use are the extent, duration, intensity, and reversibility of change. Energy-related activities often act on land cover, which can constrain potential land-use options. Energy infrastructure such as refineries, storage tanks, roads, and dams, typically replaces, inundates, or fragments vegetation across landscapes for long periods (more than 50 years). In contrast, oil and gas wells and wind turbines can have a smaller or less enduring footprint. Nonetheless, in those ecosystems where petroleum or natural-gas extraction occurs, oil spills or brine scars are frequent long-term disturbances that denude vegetation unless active restoration is conducted (Jager et al. 2005). In addition, barge and access channels dredged through wetlands for exploration and extraction, along with subsidence occurring after oil and gas extraction takes place can permanently affect topography and land cover with irreversible loss of ecosystems and wide-ranging legacy effects such as loss of protective capacity from storm surges that continue long after production operations cease (Morton et al. 2006).

The availability of inexpensive fossil fuels has been a major driver of global land-use change. The low price of fuel has enabled such diverse activities as urban sprawl, industrial forestry, large-scale steel production, and agricultural expansion (e.g., Wind and Wallender 1997). For example, energy-intensive dam construction has facilitated aluminum production, which has promoted more building construction and widespread use of materials with high imbedded energy and emissions (Fearnside 2002). Additionally, cheap fuels (and energy-intensive refrigeration and transport) have led to a transformation of the scale and location of food, feed, and fiber production, changing land-use patterns around the world by replacing local supply chains with global trade networks. Similarly, provisioning of cheap electricity for air conditioning has facilitated shifts of settlements to the sun belts of developed nations.

Exploration and extraction of fossil fuels can have large effects on the land. Coal must be mined, extracted, crushed, transported, and then burned, which results in the need for ash and waste-heat disposal, all of which affects large areas of land. Coal extraction can leave a large and persistent footprint on land and water with long-term repercussions for future uses. The United States has the world's largest recorded coal reserves, followed by the Russian Federation, China, Australia and India (World Energy Council 2010). The method by which coal is moved determines its impacts on the land and water. For example, deep mining has little effect on the land surface as compared to strip mining or mountaintop removal that removes vegetation and soil. Large forest blocks in the southern Appalachians of the United States have been converted to edge habitat through indirect effects of mountaintop-removal coal mining (Wickham et al. 2007). Moreover, coal-fired power plants use extensive land areas for storage of coal-ash slurries (NRC 2002).

Oil shale, extra heavy oil, and natural bitumen deposits such as tar sands are other forms of fossil fuel whose extraction has large effects on the land. For example, tar sands are accessed via large strip mines or open-pit techniques and processed to extract oil-rich bitumen, which is then refined into oil (BLM 2008). About 3.5 trillion barrels of oil are estimated to be in the form of discovered tar sands and extra heavy oil, and the largest deposits are located in western Canada and Venezuela, with some in the Middle East (Parks 2009). Currently, about 40% of Canada's oil production is derived from tar sands, and output is expanding rapidly. The extensive strip mines, pits, and waste lagoons associated with tar sands entail large areas of land disturbance with long-term and irreversible consequential impacts on wildlife and on air and water quality as well as greenhouse gas emissions (Parks 2009).

Electricity production necessitates the establishment of power-line corridors, and roads are a part of any power development, extraction, or transmission. These linear features often have effects on the landscape that exceed their extent. The cutting of vegetation and topographic reworking in these corridors affects species composition and land cover (Luken et al. 1992; Rescia et al. 2006). While these linear land-cover features are compatible with some land uses, such as industrial or urban areas, they are not for other uses, such as agriculture or forest lands that tend to support numerous ecosystem services. Power-line corridors and roads may occupy only a relatively small area but cause fragmentation of vegetation patterns and can have large and cumulative effects on species that inhabit that vegetation type [e.g., forest-interior bird species (Rich et al. 1994)].

Similarly in the case of natural gas and petroleum products, pipelines as well as roads must be constructed to transport the fuels from source to destination. In the United States, there are more than 4 million km of pipelines (AOPL 2009; PHMSA 2009). Pipelines are considered to be a more reliable, economical, and environmentally favorable way to transport liquid fuels than rail or trucks (AOPL 2010); however, pipelines have the potential to fragment habitats because of their linear nature, and significant spills and explosions still occur. During construction, pipelines affect land use; however, some pipelines are subsequently buried and thereby may become more compatible with multiple land uses and pose less of a threat to the ecological composition surrounding them. Some fossil-based fuels that can be moved by pipeline need to be refined before they can be transported around the world, and the refineries become part of the energy-production footprint.

Bioenergy crops can provide renewable-energy resources, but they require suitable land and management practices (Dale et al. 2010, 2011). Long-term and extensive effects occur when a land type is replaced by bioenergy crops, such as occurs if pasture land is replaced by energy-crop production (Fargione et al. 2008). Despite extensive speculation based on modeling (e.g., Keeney and Hertel 2009), empirical evidence suggests that biofuel markets have negligible influence on global deforestation trends because forest conversion is driven primarily by political and socioeconomic factors and proceeds in advance of the need for new productive land (Geist and Lambin 2002; Lambin et al. 2003; Kline and Dale 2008). Furthermore, there are several ways that bioenergy policies can reduce the extent and intensity of land-use change and its associated greenhouse gas emissions (Kline et al. 2009). Energy-crop markets create incentives to manage land for higher productivity, which results in more CO_2 sequestration compared to unmanaged and previously disturbed land. Bioenergy crops can also reduce or avoid the common practice of burning less developed lands (e.g., slash and burn), a low-cost maintenance option that contributes to greenhouse gas emissions (USAID 2009). From 330 to 430 million ha of land burn every year, mostly in sub-Saharan Africa and along tropical agricultural frontiers (Giglio et al. 2010). Appropriately managing bioenergy opportunities requires clear objectives, such as establishing bioenergy systems based on an understanding of current land-use practices; active participation of government, growers, and industry; as well as incentives appropriate for the local situation (Keam and McCormick 2008).

Land-use impacts from wind energy development include site preparation, on-site construction of turbines, and associated development of access roads and transmission lines that can cause wildlife habitat fragmentation or displacement. Wind energy is intermittent and must be backed up by other generating systems through the use of electricity grids that transport wind energy to consumers. Their overall effect on land and the environment, once installed, include visual landscape impacts that may affect neighboring land uses and values, generator noise, collision hazard to birds and bats posed by the rotating blades, and other disturbances associated with road and turbine maintenance. However, the land footprint of wind energy in terms of extent, intensity, and duration is minimal compared to most other energy sources.

Hydroelectric power is another form of renewable energy that can have a large impact on land use. The dam and resulting reservoir changes the distribution and function of both aquatic and terrestrial species, and the construction of dams instigates new settlement by the inhabitants of the flooded area. An example of the impacts of a dam is exemplified by the Three Gorges Dam in China. Although the Chinese dam should have a net benefit of preventing 50 million more tons of coal being burned annually, it is estimated that land-use effects will extend greatly beyond the impoundment area; that impact began with the relocation of an estimated 6 million people (most of whom lived off the land or river) (Gleick 2009).

Solar energy could avoid dramatic land-use change in certain situations. Passive solar designs provide space heating and have been associated with human settlement for millennia. Modern solar panels, when placed on roofs, reduce infrastructure needed for the transportation of the power generated while requiring no new land. However materials used to produce panels and associated batteries can have significant effects on land from both initial fabrication and ultimate disposal. Large-scale commercial solar farms are the current trend toward developing solar power in the United States, and the estimated solar-electric land-use requirement for the United States is significant: 181 m^2 per capita (Denholm and Margolis 2008). Like wind, solar-electric energy output is variable and needs to be integrated with other back-up or storage systems.

Effects of land use on energy

The characteristics of a landscape (e.g., soil fertility, topography, hydrology, geology, prevailing weather conditions, and current and past use) determine whether energy resources are available and whether an extractive or renewable infrastructure can be established. For example, to establish a successful system of wind energy turbines, it is necessary to have both (1) strong, steady wind flows and (2) either energy storage capability or the ability of the electricity grid to accommodate energy pulses (Johnsson 1985; Ackermann and Söder 2000).

As another example, watershed characteristics determine power possibilities. Refineries and large thermal power plants are typically located on large rivers or estuaries, where water is readily available for processing, cooling, and shipping, leading to potential land-use and zoning conflicts. Land availability for reservoirs, as well as hydraulic head (height of reservoir) and precipitation, affects the degree to which hydroelectricity can be developed as an efficient and sustainable form of energy. Furthermore, the landscape and land-use practices upslope of the reservoir determine sediment and erosion rates that affect the maintenance and storage capacity of the system. Hence, land use affects the location of hydroelectric energy projects, their operating costs and longevity, and thus the value of a project as an energy source.

Biofuels also rely upon the availability of suitable land. Competition with land used for food crops and development can affect the economic viability of planting crops for bioenergy. Prior land uses, soil characteristics, and cultivation techniques influence yields and also contribute to the economic viability of biofuels. Because of their bulk, the range of distribution of conventional bioenergy feedstocks (such as wood, grain, and chipped or baled biomass) are limited by transportation costs (Graham et al. 1997).

Land-use practices also affect the demand for energy. Industrial and urban lands have greater demand for energy than do residential, agricultural, or forested lands and thus require nearby energy sources or the means to transport energy. The largest consumption of liquid fuels is for transportation. While per capita fuel consumption is greater on farm lands, farmland's population density is relatively low. Thus some sources of energy are not economically viable for use in rural areas. Furthermore, rural settlement often lacks the energy infrastructure found in urban areas, creating demand for different types of energy resources. As a result, rural residents may use biomass or propane heat in sites that are not served by natural gas pipelines or windmills for electricity in homes that are not connected to the grid.

Societies' land-use practices and priorities affect many stages of energy development. Hence, the availability of energy resources depends on competing land uses and values. The world's remaining fossil-fuel reserves are increasingly found in remote areas (and consequently areas with few human-caused disturbances, such as the North Slope of Alaska, Siberia, the western Amazon, deep under water, or under mountaintops in Appalachia), where exploitation can conflict with other designated uses for biodiversity conservation, watershed protection, or sustainable management of productive forests and fisheries.

Effects of land use on climate change

Land use affects climate change in various ways. Burning of fossil fuels and other energy products dominates certain land uses, such as urban areas that account for about 80% of the world's carbon emissions (Grimm et al. 2008; Wu 2008). Conversions of natural ecosystems to other uses can have strong effect on greenhouse gas emissions and albedo, and thus climate change. (Albedo effects are discussed in a subsequent section as an example of the interface among energy, land use, and climate.) Weather and climate can be altered dramatically by slight changes in atmospheric conditions (Pielke et al. 1998), such as those associated with particular land-use practices and patterns. Various computational experiments have used general circulation models to show that features of landscapes can affect global climate (Charney et al. 1977; Shukla and Mintz 1982; Rowntree and Balton 1983; Lawrence and Chase 2010).

Land-use decisions can exacerbate social and economic effects of climate change. While practices like slash and burn agriculture cause an immediate release of carbon to the atmosphere, forest management and harvesting can result in increased net sequestration rates via higher productivity and long term storage of carbon in wood products such as furniture or houses. On a global basis, deforestation and land-use-change contributions to atmospheric CO_2 were highest during past centuries (Woodwell and Houghton 1977; Le Quéré et al. 2009). From

1997 to 2006, deforestation and forest degradation accounted for approximately 12% (1.2 Pg C/year) of the annual increase in concentration of atmospheric carbon dioxide, and burning of peatland accounted for another 3% (Van der Werf et al. 2009). Many land-use practices require intense use of nitrogen-based fertilizer that releases nitrous oxide (N_2O), a potent greenhouse gas, and thus also contribute to greenhouse gas emissions (NRC 2010). The increases in global atmospheric concentrations of methane and nitrous oxide have been attributed largely to the growth of agriculture and deforestation over the past 250 years (di Norcia 2008).

Land productivity is critical in estimating the effective increase of atmospheric CO_2 and how the land's ability to absorb carbon is directly affected by human management decisions as well as by climate and weather variations (IPCC 2007; Le Quéré et al. 2009). Even in seemingly pristine and remote forests, current soil and biotic distributions (and therefore carbon stocks and potential future sequestration and storage capacities) are, in large part, a product of human land-management strategies that, in the case of the Amazon, date back to pre-Columbian times (Heckenberger et al. 2003). Generally, more-productive areas have greater potential for CO_2 sequestration and release. Peatlands are a special case and land-use changes that disturb peatlands can significantly contribute to greenhouse gas emissions (Page et al. 2011).

Quantifying land-use effects on global climate is uncertain and contentious. Uncertainty in greenhouse gas emissions from agriculture, forestry, and other land-use activities is 50–100% (NRC 2010). This large uncertainty means that a large portion of the required information is poorly known or unknowable. For example, the estimated annual flux of CO_2 released through forest clearing may be off by a factor of two (NRC 2010). Major sources of uncertainty in the models that estimate the current contribution of land-use change to changes in atmospheric CO_2 are estimates of above- and below-ground biomass, rates and type of land-use change, disturbance regimes, and the fate of carbon following land-use change (Dale and King 1996; Le Quéré et al. 2009). Poor information on rates, intensities, and locations of land-use change and disturbances are the largest and most important source of uncertainty in the simulation of carbon emissions from historical land use (Dale and King 1996; NRC 2010). These uncertainties must be addressed to have confidence in estimates of how much land change contributes to atmospheric concentrations of CO_2. Furthermore, the range of CO_2 releases caused by land-use change that is commonly used in current modeling was "assigned" rather than calculated and remains the most uncertain of the components of the global carbon budget (Canadell et al. 2007). Although current uncertainty regarding the land-use-change flux estimates remains high (from 0.4 to 1.9 Pg C/year), it is much reduced from the uncertainty estimates of the 1970s of 2–22 Pg C/year (Woodwell and Houghton 1977). The reduction in uncertainty resulted from great improvements in the information base from which the estimate was obtained and from more-sophisticated computer models (Dale et al. 1991); yet, still more improvements are needed, especially in the underlying data (Grainger 2009). Furthermore, data-aggregation averaging and general circulation models leave out fine-scale spatial variations in land use and climate, which are vital in determining the effect that land use has on global climate (Pielke and Avissar 1990; Johnson and Sharma 2009). Despite many uncertainties, three trends can be observed: total climate-forcing emissions from land-use change are declining; the land-use change share of global emissions is falling faster as fossil emissions grow; and the importance of land management to optimize carbon sequestration and reduce potential climate change impacts is increasingly recognized.

Effects of energy on climate change

Energy production and use affect climate both directly and indirectly. Energy use can change the amount of CO_2 and other greenhouse gases in the atmosphere as well as heating or cooling the immediate environment. The burning of fossil fuels releases CO_2 as well as radiatively active particulate matter and NO_x (Crutzen and Andreae 1990). Carbon releases from fossil fuels are estimated to have increased by 19% between 1996 and 2006 (Marland et al. 2006). Human activities that use fossil fuel have produced more than 130 times the amount of CO_2 emitted by volcanoes and solar flares over the entire world from 1751 to 2007 (di Norcia 2008). Fossil fuels are responsible for about 88% of global CO_2 emissions (Le Quéré et al. 2009). The share of global emissions from fossil fuels is increasing as (1) economies become more fossil-energy intensive (Canadell et al. 2007; van der Werf et al. 2009) and (2) contributions from the other major anthropogenic source (land-use change) diminish as the world's forest land approach an equilibrium in biomass, with forest biomass losses being offset by new growth (FAO 2005, 2007; Kauppi et al. 2006; Grainger 2008).

In comparison to fossil fuels, renewable-energy technologies (such as wind or solar energy) and nuclear energy are closer to carbon-neutral (Barthelmie et al. 2008) and thus have a smaller effect on climate change. Even so, the creation of reservoirs for hydropower is a source of greenhouse gas release (Fearnside 1995), though they release less CO_2 per energy unit than does a coal-fired electricity generation system (Parliamentary Office of Science and Technology 2006). Moreover, perennial lignocellulosic bioenergy feedstocks can sequester carbon in the ground via their extensive root systems. For example, when planted on cleared lands, deep-rooted perennial biofuel feedstocks in tropical South America could enhance soil-carbon storage by as much as 0.5–1 metric ton ha^{-1} $year^{-1}$ (Fisher et al. 1994) with the time to saturation being dependent on land-use history, disturbance regimes, soils, and other characteristics of the system. Perennial bioenergy croplands can increase carbon sequestration significantly more than do annual crops or unmanaged scrubby vegetation. Perennial biomass feedstocks can also be combined with efforts to restore degraded lands, such as former mining sites, thus increasing carbon-storage capabilities and creating a potential fuel (IEA Bioenergy 2005). Kim et al. (2009) found that crop management is a major factor in determining greenhouse gas emissions associated with agricultural land-use change, with no-till and no-till plus cover crops substantially accelerating the greenhouse gas benefits for biofuels. Choice and availability of distribution systems can also influence emissions from energy production pathways. For example, while biofuels currently are transported by rail, truck, and barge, some of the cost and emissions associated with these transport options could be reduced by using pipelines (AOPL 2010) if corrosion (Monti et al. 2008) and product cross-contamination issues can be resolved.

While fuel combustion contributes to climate warming via greenhouse gas emissions, it also has a cooling effect via aerosols (Ming and Ramaswamy 2009). Persistent haze in industrialized nations consists of various particulates, sulfur dioxide, smoke, and organic gases largely produced by the burning of fossil fuels (especially coal) and vegetation. These emissions are increasing in most industrializing nations of the Northern Hemisphere with the exception (currently) of the United States (IPCC 2007). Climate forcing by anthropogenic aerosols occurs in the daytime, predominantly in the summer, and generally downwind of sources. Yet the widespread distribution of aerosols leads to hemispheric or even global effects. Countering aerosol cooling effects, black-carbon particles (soot) contribute to warming. More data and improved modeling will help sort out the complex interactions over time, but the net cooling effect of aerosols are lower than the multiple warming forces.

Effects of climate change on land use

Climate change can have dramatic effects on the extent, productivity, and potential uses of land. Sea-level rise is one effect with direct impacts on land use. Estimates of global mean sea-level rise between 1990 and the 2080s range from 22 to 34 cm (Nicholls 2004). Because 40% of the world's population lives within 100 km of a coast (Small and Nicholls 2003), rising water levels impact the ability to grow crops in specific regions and to maintain suitable living conditions. Furthermore, the poorest residents are at greatest risk from flooding because they often settle in floodplains and other hazard-prone locations because more-suitable alternatives are not affordable (Hardoy et al. 2001).

Climate change can also influence which crops or trees can be grown in specific areas and the risks of losses in agricultural and forest systems. Rockström et al. (2009) point out that carbon dioxide concentrations exceeding 350 parts per million by volume or radiative forcing exceeding 1 W/m^2 above pre-industrial levels substantially increases the risk of irreversible and abrupt shifts in forest and agricultural systems, and yet those values rose to 391 ppm and more than 1.5 W/m^2, respectively, by January 2011

(US Department of Commerce 2011). Changing rainfall patterns, floods, and droughts can affect urban, industrial, and agricultural activities and, as competition for water increases, could impose severe limitations on future growth (Sun et al. 2008).

Climate affects land use, and thus changes in climate can instigate changes in the location and intensity of use patterns. Human settlements and industries have been strongly influenced by climatic factors. For example, the locations of the world's fisheries and fishing communities as well as agricultural settlements are largely a climate-driven phenomenon. Sunny and mild weather is amenable to low-energy living conditions. Recent studies have projected or confirmed the interactions between climate change and land use. For example, climate change is increasing the risk of flooding as well as causing other environmental damage in coastal areas prompting population shifts away from high-risk areas (IPCC 2007). Climate vulnerability and extreme events often drive human migration into other regions, resulting in additional land-use change.

The close relationship between land use and climate change can create especially difficult situations for rural populations that depend on local resources. For example, vulnerabilities to climate change occur in parts of the Brazilian Amazon rainforest (Werth and Avissar 2002) where native tribes are facing a shrinking food source from streams and agricultural instability because of flooding and irregular rainfall patterns. About 13,000 km^2 of rainforest have been cut down since the 1970s, and the flora relied upon by tribes has changed as a result of clear-cutting. These changes have also increased the vulnerability to forest fires (Lindenmayer et al. 2009).

Effects of climate change on energy

Climate change influences energy through its effects on demand, distribution, intensities, and types of energy that are available and being used (Wilbanks et al. 2007). For example, as climate changes, so do patterns of energy use, with increasing demand for air conditioning as temperatures increase and increasing demand for heating when temperatures fall. The type of energy demand is also influenced by climate. Electrical air-exchange heat-pump systems are appropriate for climates with moderate heating and cooling needs, whereas gas furnaces operate more efficiently under long durations of cold weather. Distributed solar power and wind power may become more viable in regions with extreme climates (such as hot, dry, or windy sites). However, these places are often distant from where the energy is needed and thus may require establishment of infrastructure to transport the energy. Furthermore, because oil supplies rely on ports and nearby refineries, increases in storm intensity produced by climate change can disrupt supplies within a given region or nation, as evidenced by Hurricane Katrina in the United States in 2005.

Climate and, therefore, climate change affect bioenergy options. Temperatures and precipitation interact with soil and other aspects of location to determine what types of bioenergy feedstock crops can be grown. Growing conditions are one factor that affects the economic viability of biofuels. Where climate favors higher yields, bioenergy crops are likely to be more competitive. Furthermore, much of the existing stock of energy infrastructure in the world is dependent upon water—a very climate-sensitive resource. Sandia's Energy Water Roadmap (Sandia National Laboratory 2007) suggests water resource availability is likely to be a major determinant of future energy development in the United States. If climate changes, then energy options change as well.

Hydropower is particularly vulnerable to changes in precipitation patterns (Markoff and Cullen 2008). For example, low water flow can increase the frequency and extent of times when water turbines cannot operate. In areas that rely on hydroelectric power, fluctuations in precipitation and evaporation rates can impact energy output from dams. For example, in California, during the winter and spring when precipitation is the heaviest, hydroelectric dams have their greatest electrical output. However, in most regions, peak electricity demand occurs during the hot season when precipitation is lower. Further decreases in precipitation, shifting of springtime peak flows to wintertime, and increases in evaporation because of climate change would ultimately affect the efficiency of hydroelectric power (Vicuna et al. 2008).

The land use–climate change–energy nexus

Heretofore, we have presented interactions between pairs of land use, climate change, and energy; but clearly each pair interacts with the third force, as well. Numerous contingencies involving all three factors, as well as feedbacks, exist in this tripartite system. More specifically, land use, climate change, and energy development and use influence or drive ecosystem services, which also influence land use, climate change, and energy. Sensitive ecosystems are affected by land use, climate, and energy availability; and changes in those ecosystems can affect land use, global climate, and energy choices. For example, disturbance frequency and severity can be altered by climate change, land-use change, and energy choices; and disturbances like fire can influence these components, as well. Similarly, the three components all influence albedo and latent heat, which are also factors in determining the amount and nature of climate change. The examples of ecosystem services, sensitive ecosystems, albedo, and disturbances are discussed below to illustrate potential interactions that are best assessed through an integrative research approach.

Ecosystem services

The term ecosystem services refers to a range of environmental benefits that are provided to humanity by natural and managed ecosystems (Millennium Ecosystem Assessment 2005). These benefits include clean water, air, food, and natural resources broadly considered (e.g., sunlight and wind) both within a region and across the entire globe. Ecosystem services are in the nexus of the tripartite system because they are affected by land-use practices, climate change, and energy choices.

A fundamental concern is how to meet current needs for energy and land while maintaining services vital for human welfare in the long term. Reliance on fossil energy permanently removes options of incalculable value for future generations while adding stress to the ecosystems needed for the current provision of services. Analysis of energy alternatives should consider potential feedbacks that affect future energy and land-use options as well as climate. For example, environmental considerations of bioenergy include services that are provided by prevailing ecological conditions (such as soil, water, and air quality), by biodiversity, by plant and wildlife habitat, and by storm-water protection (all of which are influenced by both climate change and land-use practices). In addition, the net flux of greenhouse gases resulting from local energy decisions can affect atmospheric carbon concentrations and climate forcing at large scales.

Sensitive ecosystems

Sensitive ecosystems are those at topographic or climatic margins, such as coastal zones or arctic regions, and areas with valuable attributes that can change radically in response to small disturbances. Sea-level rise (resulting from climate change) will have a huge effect on coastal and low-lying lands; yet it is unclear what these changes imply for future land use via the displacement of activities into new areas and potentially into other sensitive ecosystems. When energy exploration and extraction occur in fragile ecosystems (e.g., boreal forests or coastal zones), then adverse impacts become complex and difficult to mitigate or to restore.

Changes in energy and land use in peat ecosystems illustrate an important set of interactions. Approximately one-third of the total world pool of soil carbon is sequestered in peatlands, and thawing permafrost (caused by climate change, land-use change for energy production, or climate-facilitated fire events) releases significant amounts of methane and CO_2 (Walter et al. 2006). Even though peatlands can be considered renewable under the right conditions and over long time spans, a typical rate of peat accumulation of less than a millimeter per year (Gorham 1991) means that a multi-millennial time frame is required for their eventual restoration.

Freshwater ecosystems are sensitive to energy, land-use and climate interactions. Land use is governed, in part, by land value, which is a function of biophysical factors (soils, slope), prevailing climate; access to energy and freshwater; view-shed characteristics; and past, present, and neighboring land uses. The intensity of land use and energy use often increases around freshwater resources as land values rise, leading to feedbacks affecting climate and future land values and productive use options.

Albedo

Albedo of a surface is defined as the ratio of diffusely reflected to incident electromagnetic radiation and conveys how much an object reflects light. Albedo can be a major mechanism by which the Earth's surface influences climate. Experiments using general circulation models have shown the significant role that albedo can play in climate change (Pielke and Avissar 1990). Fossil-energy production can alter albedo through aerosol generation and land-use change, such as disturbance from mining. Combustion of any fuel can create soot and black carbon that affects albedo. Climate change can alter albedo through changes in cloud cover and the amount, timing, and persistence of snow and ice (which are a function of temperature and precipitation conditions). These factors, in turn, feed back to climate. Land use significantly impacts albedo because biotic and abiotic factors that characterize land use have different light reflectivities. Fresh snow is the most effective naturally occurring reflector, while black soot, open water and coniferous forests are among the least reflective. Land use–climate interactions can affect total albedo not only by radically changing the albedo of a portion of the Earth's surface but also by altering the area and distribution of reflective surfaces, temperature differentials, and wind currents. Land-use change, such as aforestation, could have very different effects on albedo, depending on where it occurs. In temperate regions with snowfall, for example, clearing pine forests is predicted to have a cooling effect from increased albedo associated with the snow cover (Rosenzweig et al. 2008), whereas clearing forests in tropical areas can have the opposite effect on albedo and increase latent heat. In urban settings, energy-efficiency strategies that employ white or reflective roofing not only keep buildings cooler during warm months but also increase the albedo and thereby reduce contributions to latent heat and the urban heat island phenomenon.

Disturbances

Changes in disturbance frequency, extent, and intensity can occur as a result of climate change, land-use practices, energy use, and interactions among these factors. In addition, disturbance frequency and severity have major effects on subsequent land and energy use (Dale 1997) and can also affect climate forcing. These disturbances include floods; fires; ice storms; severe wind and dust storms; tornadoes; hurricanes; and outbreaks of pests, disease, and invasive species that alter species structure and landscapes (Dale et al. 2001). For example, insect pests can spread as the result of trade, transport of fuel wood, or just hitchhiking on vehicles. Increased hurricane frequency putatively caused by climate change has major impacts on current fossil-energy refining and distribution industries, as well as potential impacts on future renewable technologies in coastal zones, such as wind energy, bioenergy, and wave-action energy.

Major and minor disturbances interact with human-induced effects on the environment, such as air pollution and land-use change. The extent and intensity of disturbances are often functions of both natural and human conditions. For example, the extent of impacts from forest fires and floods are the products of weather events combined with land-use practices (Booth et al. 2002; Meierdiercks et al. 2010). Historically, long-term reliance on wood fuels led to the deforestation of many island nations and areas around urban centers, which increased the likelihood of landslides, flooding, and other disturbances with ripple effects on energy supplies, use and climate.

Invasive species include both indigenous and non-native species that have traits allowing them to spread widely and rapidly; and their distribution and abundance are often influenced by land-use change, climate, and energy. For example, the mountain pine beetle (*Dendroctonus ponderosae*) currently found in mountain pine forests of North America has had a population surge since 2000, bringing its relationship with the pine from a mutual relationship to a parasitic one. The mountain pine beetles no longer focus on nesting in unhealthy pines that allow for forest population control. With milder winters (apparently a climate change effect) supporting an expanded population and other environmental stresses on vegetation (including pollution from fossil fuels), the beetles have infested entire regions, leading to eventual changes in land cover (e.g., from forest to meadow or from coniferous to hardwood) and other disturbance patterns (fire), which, in turn, influence land-use options and greenhouse gas emissions. At the current rate of spread in British Columbia, Canada, 80% of the mature pine will be dead by 2013 (Safranyik and Wilson 2006).

Other anthropogenic forces influencing the nexus

Technology can have a catalytic effect on land-use change and energy use that interfaces with climate.

For example, crop yields may increase with new technology, allowing bioenergy feedstocks to be produced with the use of less land and with potentially greater net carbon sequestration (Keeney and Hertel 2009). As another example, 50 years ago, less than one-third of Americans lived in the southern portion of the United States; today, half of the population resides in the South largely because of air conditioning. Air conditioning has allowed for urban and suburban expansions into areas previously considered unfavorable or unhealthy, accelerated the clearing of forests and wildlands, and greatly increased energy intensity per capita. As automobiles displace bicycles around the globe, they are driving up (literally) the consumption of liquid transportation fuels, the net energy embodied by the vehicle, the construction of paved roads and highways, emissions of CO_2, and the production of other radiatively active gases (i.e., sulfur dioxide, ground-level ozone, and particulate pollutants). These changes result in consumption of additional fossil fuels for air conditioning in autos and create incentives to run motors more on hot days.

The density, movement, culture, and social norms of human populations can influence climate-change forcing, land use, and energy use, particularly via the demand for resources and services. For example, population growth has had profound ecological effects on coastal habitats. The state of Florida, which relies on tourism as a key industry, has experienced overdevelopment of coastal areas, resulting in the loss of ecosystem services and property values (Finkl and Charlier 2003). The loss of natural barriers, including the loss of wetlands because of access channels and subsidence associated with fossil-fuel extraction, increases the natural risk presented by storms (Costanza et al. 2008). Larger populations along coasts mean that more people are at risk from coastal storms, land and seabed subsidence, sea-level rise, and spills from increasing fossil fuel development and offshore shipping.

Economic factors also affect climate change, land use, and energy. Rapid growth rates in emerging economies drive global demand for energy and land, with resulting implications for climate change. The primary barrier to market penetration for many renewable sources of energy is cost. For example, it has been estimated that China's wind energy potential is equivalent to all of the energy demand growth in China projected to 2030 if the guaranteed price per kilowatt-hour were adequate (McElroy et al. 2009). Global energy markets and the lack of any social costs assigned to greenhouse gas emissions (and the unique opportunity costs of nonrenewable fuels) have kept the prices of fossil-fuel-derived electricity and other commercial fuels relatively low, making it difficult for cleaner, renewable sources of energy to compete.

Conclusions: Practical needs and research for landscape ecology related to the interfaces among land use, climate change, and energy

Some energy sources, if properly planned and managed, can be associated with compatible land uses. Natural gas and oil extraction can often co-occur with cattle and bison grazing, nature preserves, or recreational activities. Coal extraction may be compatible with timber extraction and recreation. Wind energy may be compatible with agriculture and grazing. And solar energy is compatible with many structures in the built environment. Developing robust and diverse land-use and bio-production systems that are integrated to produce food, feed, fuel, fiber, and other materials and designed to be adaptable to climatic variations represent important steps toward a strategy that addresses climate-change and energy-security. The challenge is to proactively design integrated energy and land-use systems that can meet the needs of today without compromising the welfare of tomorrow.

Landscape ecology can enhance understanding of the interactions among land use, energy, and climate change. Practical applications and theories of causes and effects of land-use change should consider how climate change and energy use can influence land-use practices and future land-use options. The current state of the art reflected in scientific literature suggests that more research is needed in at least eight areas.

(1) Landscape designs need to be developed for energy production in the context of other services from the land and predicted climate change (*a la* Nassauer and Opdam 2008; Dale et al. 2011). Modeling tools can be used to develop, assess, and visualize potential

landscapes and their effects (e.g., see Gaucherel et al. 2010).

(2) It is important to determine how climate change will alter landscapes and conditions for the sustained production of food, feed, fiber, fodder, and fuel feedstocks. This need can be addressed by focusing on relationships between pattern and process at a range of relevant scales (see Opdam et al. 2009).

(3) Planners and policymakers need case studies that provide examples and illustrate opportunities to integrate land-management systems to achieve multiple large-scale objectives. These demonstrations will permit prioritization of local social and environmental goals, analysis of tradeoffs, and development of approaches designed to optimize productive land management with the use of systems approaches (Robertson et al. 2008; Bogdanski et al. 2010).

(4) Effects of energy development and use, land-use change, and climate change need to be compared with a suite of indicators and relevant information across the full life cycle of these stressors. In contrast to that approach, use of fossil fuels is often compared to use of renewable energy based only on estimates of greenhouse gas emissions per unit of fuel produced (e.g., Ceq per MJ). When considering the land-energy-climate nexus, this approach is inadequate, incomplete, and inappropriate. Nevertheless, the US Environmental Protection Agency (EPA) (for the Renewable Fuel Standard analysis) and the State of California (for the Low Carbon Fuel Standard regulation) both assumed effects of fossil fuels on land and land opportunities were insignificant because well-sites are small relative to the energy produced (minimal Ceq per MJ). Hence, the effects of millions of kilometers of roads and seismic lines that were inserted into remote habitats (from the Amazon to the boreal forests), along with the loss of mangroves, salt-water marshes, and threatened wetland habitats from Angola to Louisiana, were all considered insignificant relative to the amount of energy derived. This approach to quantify effects of energy development must be corrected. First, the effects on land and climate of fossil-energy exploration, production, and use need to be better quantified and understood. The concept of “landscape services” can provide a useful way to address both valuation needs and to communicate with diverse stakeholders (Termorshuizen and Opdam 2009). Second, the location of lands affected as well as the intensity, duration, extent, and reversibility of effects need consistent analysis using functional units for comparison that reflect environmental and social priorities. Third, the intrinsic value of fossil fuels left in the ground needs to be considered not only as an opportunity cost to future generations, but also as a direct withdrawal of value from current accounts. Fourth, the energy value of millions of years of biotic growth, decomposition, heat, and pressure would need to be included in an equation to equitably compare the total embedded energy in fossil fuels with that in renewable fuel alternatives today.

(5) Local and regional processes and drivers of first-time land-use change need to be characterized and modeled. This effort might build upon the landscape approach presented by Sohl et al. (2010) under which regional models of secondary land change include geographic setting, land-use history, and drivers of change that represent local land-use patterns.

(6) Sustainability benefits and metrics for different feedstock crops need to be documented. Agreeing on specific indicators of environmental change that can be affected is a first step (see McBride et al. 2011). Data for these measures need to be collected at relevant scales and compared to threshold or target values in order to interpret potential changes.

(7) It is important to identify the spatial and temporal resolution at which it is appropriate to assess and manage land-use effects on climate change, energy, and other factors [such as Weishampel et al. (1999) has done for soil processes]. A related step is to improve our understanding of current land uses and the implications for current and future carbon storage and release, as well as the extent and availability of underutilized lands that are suitable for bioenergy crops, wind farms, hydroelectric projects, solar panels, nuclear power plants, or other energy sources with minimal impacts on ecosystem services (e.g.,

see Van Doorn and Bakker 2007). Landscape-ecology approaches permit analysis of land-use options to address a diverse set of social needs (e.g., see Atwell et al. 2009).

(8) Finally, quantitative tools need to be developed that can estimate indirect effects of energy use, land-use change, and climate change at appropriate scales. Together, these approaches can be used to address the relationship among land use, climate change, energy, food security, and poverty—a pressing concern that also falls within the purview of landscape ecology (Pijanowski et al. 2010).

Land use, climate change, and energy influence each other through a complex set of processes and feedback loops that remain to be properly documented, modeled, and calibrated. Landscape ecology can provide decision makers with information on benefits and costs resulting from choices about the spatial location of energy choices in terms of impact intensity, extent, longevity, and likely interactions that may compound or offset some effects. Opportunity costs must also be considered in deciding where to use land for energy, agriculture, or human habitation and if and when to draw down further on fossil reserves. Decisions should be based on scientific study and evidence of environmental, social, and economic tradeoffs and should consider both the short-term and long-term implications of climate change, land use, and energy production and use in an integrated fashion.

Acknowledgments This research was supported by the U.S. Department of Energy (DOE) under the Office of the Biomass Program. Oak Ridge National Laboratory is managed by the UT-Battelle, LLC, for DOE under contract DE-AC05-00OR22725. We thank Arielle Notte and Christen Donald for helping us synthesize background information. Frederick O'Hara edited the manuscript, and Jennifer Smith checked some references. Ben Preston, Paul Opdam, Jianguo Wu, and two anonymous reviewers provided useful comments in reviews of an earlier draft of the manuscript.

References

Ackermann T, Söder L (2000) Wind energy technology and current status: a review. Renew Sustain Energy Rev 4:315–374

Ahn J, Brook EJ (2008) Atmospheric CO_2 and climate on millennial time scales during the last glacial period. Science 322:83–85

AOPL (Association of Oil Pipe Lines) (2009) 2007 Shifts in petroleum transportation. http://www.aopl.org/pdf/Shift_Report_Posted_September_2_20091.pdf. Accessed September 2010

AOPL (Association of Oil Pipe Lines) (2010) Ethanol, biofuels, and pipeline transportation. http://www.aopl.org/pdf/AOPL_API__Ethanol_Transportation_March_2010.pdf. Accessed September 2010

Atwell RC, Schulte LA, Westphal LM (2009) Landscape, community, countryside: linking biophysical and social scales in US Corn Belt agricultural landscapes. Landscape Ecol 24:791–806

Barthelmie RJ, Morris SD, Schechter P (2008) Carbon neutral Biggar: calculating the community carbon footprint and renewable energy options for footprint reduction. Sustain Sci 3:267–282

Baumert KA, Herzog T, Pershing J (2005) Navigating the numbers: greenhouse gas data and international climate policy. World Resources Institute. http://www.wri.org/publication/navigating-the-numbers. Accessed April 2011

BLM (Bureau of Land Management) (2008) Oil shale and tar sands final programmatic environmental impact statement (PEIS). FES 08-32. U.S. Department of the Interior, Washington, DC. http://ostseis.anl.gov/documents/fpeis/index.cfm. Accessed September 2010

Bogdanski A, Dubois O, Jamieson C, Rainer K (2010) Making integrated food-energy systems work for people and climate. Environment and natural resources management working paper #45. Food and Agriculture Organization of the United Nations, FAO, Rome

Booth DB, Hartley D, Jackson R (2002) Forest cover, impervious-surface area, and the mitigation of storm water impacts. J Am Water Resour Assoc 38:835–947

Briones MJI, Ostle NJ, McNamara NR, Poskitt J (2009) Functional shifts of grassland soil communities in response to soil warming. Soil Biol Biochem 41:315–322

Canadell JG, Le Quéré C, Raupach MR, Field CB, Buitenhuis, ET, Ciais P, Conway TJ, Gillett NP, Houghton RA, Marland G (2007) Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proc Natl Acad Sci USA 104(47):18866–18870

Charney J, Quirk WJ, Chow SH, Kornfield J (1977) Comparative study of effects of albedo change on drought in semi-arid regions. J Atmos Sci 34(9):1366–1385

Costanza R, Perez-Maqueo O, Martinez ML, Sutton P, Anderson SJ, Mulder K (2008) The value of coastal wetlands for hurricane protection. Ambio 37:241–248

Crutzen PJ, Andreae MO (1990) Biomass burning in the tropics: impact on atmospheric chemistry and biogeochemical cycles. Science 250:1669–1678

Dale VH (1997) The relationship between land-use change and climate change. Ecol Appl 7:753–769

Dale VH, King AW (1996) Implications of uncertainty in land-use change for global terrestrial CO_2 flux. In: Korpilahti E, Mikkela H, Salpnen T (eds) Caring for the forest: research in a changing world. International Union of

Forestry Research Organizations XX World Congress report, vol II. Gummerus Printing, Jyvaskyla, pp 284–293

Dale VH, Houghton RA, Hall CAS (1991) Estimating the effects of land-use change on global atmospheric CO_2 concentrations. Can J For Res 21:87–90

Dale VH, Joyce LA, McNulty S, Neilson RP, Ayres MP, Flannigan MD, Hanson PJ, Irland LC, Lugo AE, Peterson CJ, Simberloff D, Swanson FJ, Stocks BJ, Wotton BM (2001) Climate change and forest disturbances. Bioscience 51:723–734

Dale VH, Fargione J, Kline K, Wiens J (2010) Biofuels: implications for land use and biodiversity. Biofuels and sustainability report of the Ecological Society of America. http://www.esa.org/biofuelsreports. Accessed March 2011

Dale VH, Wright L, Kline KL, Perlack R, Graham RL, Downing M (2011) Interactions between bioenergy feedstock choices and landscape dynamics and land use. Ecol Appl 21(4):1039–1054

Denholm P, Margolis RM (2008) Land-use requirements and the per-capita solar footprint for photovoltaic generation in the United States. Energy Policy 36:3531–3543

di Norcia V (2008) Global warming is man-made: key points in the International Panel on Climate Change 2007 report. Oxford University Press, Cambridge

Dickinson RE (1991) Global change and terrestrial hydrology: a review. Tellus 43 AB:176–181

FAO (Food and Agriculture Organization of the United Nations) (2005) Global forest resources assessment 2005: progress towards sustainable forest management. FAO forestry paper 147. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/forestry/fra2005/en/. Accessed September 2010

FAO (Food and Agriculture Organization of the United Nations) (2007) Forestry paper 151. FAO, Rome. Fire management—global assessment 2006. A thematic study. ftp://ftp.fao.org/docrep/fao/009/A0969E/A0969E02.pdf. Accessed March 2011

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. Science 319:1235–1238

Fearnside PM (1995) Hydroelectric dams in the Brazilian Amazon as sources of "greenhouse" gases. Environ Conserv 22:7–19

Fearnside PM (2002) Avanca Brasil: environmental and social consequences of Brazil's planned infrastructure in Amazonia. Environ Manag 30:735–747

Finer M, Orta-Martinez M (2010) A second hydrocarbon boom threatens the Peruvian Amazon: trends, projections, and policy implications. Environ Res Lett 5:014012

Finer M, Moncel R, Jenkins CN (2010) Leaving the oil under the Amazon: Ecuador's Yasuni-ITT initiative. Biotropica 42:63–66

Finkl CW, Charlier RH (2003) Sustainability of subtropical coastal zones in southeastern Florida: challenges for urbanized coastal environments threatened by development, pollution, water supply, and storm hazards. J Coast Res 19:934–943

Fisher MJ, Rao IM, Ayarza MA, Lascano CE, Sanz JI, Thomas RJ, Vera RR (1994) Carbon storage by introduced deep-rooted grasses in the South America savannas. Nature 371:236–238

Forman RTT (1995) Land mosaics: the ecology of landscapes and regions. Cambridge University Press, Cambridge

Gaucherel C, Griffon S, Misson L, Houet T (2010) Combining process-based models for future biomass assessment at landscape scale. Landscape Ecol 25:201–215

Geist HJ, Lambin EF (2002) Proximate causes and underlying driving forces of tropical deforestation. Bioscience 52: 143–150

Giglio L, Randerson JT, van der Werf GR, Kasibhatla PS, Collatz GJ, Morton DC, De Fries RS (2010) Assessing variability and long-term trends in burned area by merging multiple satellite fire products. Biogeosciences 7: 1171–1186

Gleick P (2009) Three Gorges Dam Project, Yangtze River, China. Water Brief 3. http://www.worldwater.org/data20082009/WB03.pdf. Accessed February 2011

Gorham E (1991) Northern peatlands: role in the carbon cycle and probable responses to climatic warming. Ecol Appl 1:182–195

Graham RL, Liu W, Downing M, Noon CE, Daly M, Moore A (1997) The effect of location and facility demand on the marginal cost of delivered wood chips from energy crops: a case study of the state of Tennessee. Biomass Bioenergy 13(3):117–123

Grainger A (2008) Difficulties in tracking the long-term global trend in tropical forest area. Proc Natl Acad Sci USA 105:818–823

Grainger A (2009) Measuring the planet to fill terrestrial data gaps. Proc Natl Acad Sci USA 106:20557–20558

Grimm NB, Faeth SH, Golubiewski NE, Redman CL, Wu JG, Bai XM, Briggs JM (2008) Global change and the ecology of cities. Science 319:756–760

Gupta AK (2004) Origin of agriculture and domestication of plants and animals linked to early Holocene climate amelioration. Curr Sci 87:54–59. http://www.ias.ac.in/currsci/jul102004/54.pdf. Accessed February 2011

Hardoy JE, Mitlin D, Satterthwaite D (2001) Environmental problems in an urbanizing world. Earthscan, London

Hays JD, Imbrie J, Shackleton N (1976) Variations in the Earth's orbit: pacemaker of the ice ages. Science 194: 1121–1132

Heckenberger MJ, Kuikuro A, Kuikuro UT, Russell JC, Schmidt M, Fausto C, Franchetto B (2003) Amazonia 1492: pristine forest or cultural parkland? Science 301: 1710–1714

IEA Bioenergy (2005) Benefits of bioenergy. http://www.ieabioenergy.com/LibItem.aspx?id=179. Accessed September 2010

International Energy Agency (IEA) (2010) Key world energy statistics. IEA, Paris. www.iea.org. Accessed March 2011

IPCC (Intergovernmental Panel on Climate Change) (2007) Climate change 2007: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fourth Assessment. Oxford University Press, London

Jager HI, Efroymson RA, Sublette KL, Ashwood TL (2005) Unnatural landscapes in ecology: generating the spatial distribution of brine spills. Environmetrics 16:687–698

Johnson FM, Sharma A (2009) GCM simulations of a future climate: how does the skill of GCM precipitation simulations compare to temperature simulations? In: 18th World IMACS/MODSIM Congress, Cairns, Australia

13–17, 2009. http://www.mssanz.org.au/modsim09/G2/johnson_fm_G2.pdf. Accessed October 2010

Johnsson GL (1985) Wind energy systems. Prentice Hall, Englewood Cliffs

Kauppi PE, Ausubel JH, Fang JY, Mather AS, Sedjo RA, Waggoner PE (2006) Returning forests analyzed with the forest identity. Proc Natl Acad Sci USA 103:17574–17579

Keam S, McCormick N (2008) Implementing sustainable bioenergy production: a compilation of tools and resources. International Union for Conservation of Nature, Gland

Keeney R, Hertel TW (2009) The indirect land use impacts of United States biofuel policies: the importance of acreage, yield, and bilateral trade responses. Am J Agric Econ 91:895–909

Kim H, Kim S, Dale BE (2009) Biofuels, land-use change, and greenhouse gas emissions: some unexplored variables. Environ Sci Technol 43:961–967

Kline KL, Dale VH (2008) Biofuels, causes of land-use change, and the role of fire in greenhouse gas emissions. Science 321:199

Kline KL, Dale VH, Lee R, Leiby P (2009) In defense of biofuels, done right. Issues Sci Technol 25(3):75–84

Lambin EF, Geist HJ, Lepers E (2003) Dynamics of land-use and land-cover change in tropical regions. Annu Rev Environ Resour 28:205–241

Laurance WF, Croes BM, Tchignoumba L, Lahm SA, Alonso A, Lee ME, Campbell P, Ondzeano C (2006) Impacts of roads and hunting on central African rainforest mammals. Conserv Biol 20:1251–1261

Lawrence PJ, Chase TN (2010) Investigating the climate impacts of global land cover change in the community climate system model. Int J Climatol 30:2066–2087

Le Quéré C, Raupach MR, Canadell JG, Marland G, Bopp L, Ciais P, Conway TJ, Doney SC, Feely RA, Foster P, Friedlingstein P, Gurney K, Houghton RA, House JI, Huntingford C, Levy PE, Lomas MR, Majkut J, Metzl N, Ometto JP, Peters GP, Prentice IC, Randerson JT, Running SW, Sarmiento, JL, Schuster U, Sitch S, Takahashi T, Viovy N, van der Werf GR, Woodward FI (2009) Trends in the sources and sinks of carbon dioxide. Nat Geosci 2:831–836

Lindenmayer DB, Hunter ML, Burton PJ, Gibbons P (2009) Effects of logging on fire regimes in moist forests. Conserv Lett 2:271–277

Luken JO, Hinton AC, Baker DG (1992) Response of woody plant communities in power-line corridors to frequent anthropogenic disturbance. Ecol Appl 2:356–362

MacMynowski DP, Root TL (2009) Climate and the complexity of migratory phenology: sexes, migratory distances, and arrival distributions. Int J Biometeorol 51:361–373

Markoff MS, Cullen AC (2008) Impact of climate change on Pacific Northwest hydropower. Clim Chang 87:451–469

Marland G, Boden TA, Andres RJ et al (2006) Global, regional, and national fossil fuel CO_2 emissions. In: Trends: a compendium of data on global change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge. http://cdiac.ornl.gov/trends/trends.htm. Accessed February 2011

McBride A, Dale VH, Baskaran L, Downing M, Eaton L, Efroymson RA, Garten C, Kline KL, Jager H, Mulholland P, Parish E, Schweizer P, Storey J (2011) Indicators to support environmental sustainability of bioenergy systems. Ecol Indic 11:1277:1289

McElroy MB, Lu X, Nielsen CP, Wang YX (2009) Potential for wind-generated electricity in China. Science 325:1378–1380

Meierdiercks KL, Smith JA, Baeck ML, Miller AJ (2010) Analysis of urban drainage network structure and its impact on hydrologic response. J Am Water Resour Assoc 46:932–943

Millennium Ecosystem Assessment (2005) Ecosystems and human well-being: general synthesis. Island Press, Washington, DC

Ming Y, Ramaswamy V (2009) Nonlinear climate and hydrological responses to aerosol effects. J Clim 22:1329–1339

Monti A, Di Virgilio N, Venturi G (2008) Mineral composition and ash content of six major energy crops. Biomass Bioenergy 32:216–223

Morton RA, Bernier JC, Barras JA (2006) Evidence of regional subsidence and associated interior wetland loss induced by hydrocarbon production, Gulf Coast region, USA. Environ Geol 50:261–274

Musacchio LR (2009) The scientific basis for the design of landscape sustainability: a conceptual framework for translational landscape research and practice of designed landscapes and the six Es of landscape sustainability. Landscape Ecol 24:993–1013

Nassauer JI, Opdam P (2008) Design in science: extending the landscape ecology paradigm. Landscape Ecol 23:633–644

Nicholls RJ (2004) Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socioeconomic scenarios. Glob Environ Chang 14:69–86

NOAA (National Oceanic and Atmospheric Administration) (2010) Extreme events. http://www.economics.noaa.gov/?goal=weather&file=events/. Accessed October 2010

NRC (National Research Council) (2002) Coal waste impoundments: risks, responses, and alternatives. National Research Council, Washington, DC

NRC (National Research Council) (2010) Verifying greenhouse gas emissions: methods to support international climate agreements. National Academies Press, Washington, DC

Opdam P, Luque S, Jones KB (2009) Changing landscapes to accommodate for climate change impacts: a call for landscape ecology. Landscape Ecol 24:715–721

Page SE, Rieley JO, Banks CJ (2011) Global and regional importance of the tropical peatland carbon pool. Glob Chang Biol 17:798–818

Parks N (2009) The price of tar sands oil. Front Ecol Environ 7:232

Parliamentary Office of Science and Technology (2006) Carbon footprint of electricity generation. Parliamentary Office of Science and Technology, Number 268, London. http://www.parliament.uk/documents/post/postpn268.pdf. Accessed September 2010

Perlin J (1989) A forest journey: the role of wood in the development of civilization. Harvard University Press, Cambridge

PHMSA (Pipeline and Hazardous Materials Safety Administration) (2009) Pipeline basics. U.S. Department of Transportation, Washington, DC. http://primis.phmsa.dot.gov/comm/PipelineBasics.htm?nocache=4627. Accessed September 2010

Pielke RA, Avissar R (1990) Influence of landscape structure on local and regional climate. Landscape Ecol 4:133–155

Pielke RA, Avissar R, Raupach M, Dolman AJ, Zeng XB, Denning AS (1998) Interactions between the atmosphere and terrestrial ecosystems: influence on weather and climate. Glob Chang Biol 4:461–475

Pijanowski BC, Iverson LR, Drew CA, Bulley HNN, Rhemtulla JM, Wimberly MC, Bartsch A, Peng J (2010) Addressing the interplay of poverty and the ecology of landscapes: a grand challenge topic for landscape ecologists? Landscape Ecol 25:5–16

Raupach MR, Marland G, Ciais P, Le Quere C, Canadell JG, Klepper G, Field CB (2007) Global and regional drivers accelerating CO_2 emissions. Proc Natl Acad Sci USA 104:10288–10293

Rescia AJ, Astrada EN, Bono J, Blasco CA, Meli P, Adamoli JM (2006) Environmental analysis in the selection of alternative corridors in a long-distance linear project: a methodological proposal. J Environ Manag 80:266–278

Rich AC, Dobkin DS, Niles LJ (1994) Defining forest fragmentation by corridor width—the influence of narrow forest dividing corridors on forest-nesting birds in southern New Jersey. Conserv Biol 8:1109–1121

Robertson GP, Dale VH, Doering OC, Hamburg SP, Melillo JM, Wander MM, Parton WJ, Adler PR, Barney JN, Cruse RM, Duke CS, Fearnside PM, Follett RF, Gibbs HK, Goldemberg J, Mladenoff DJ, Ojima D, Palmer MW, Sharpley A, Wallace L, Weathers KC, Wiens JA, Wilhelm WW (2008) Sustainable biofuels redux. Science 322(5898):49–50

Rockström J, Steffen W, Noone K, Persson A, Chapin FS, Lambin EF, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ, Nykvist B, de Wit CA, Hughes T, van der Leeuw S, Rodhe H, Sorlin S, Snyder PK, Costanza R, Svedin U, Falkenmark M, Karlberg L, Corell RW, Fabry VJ, Hansen J, Walker B, Liverman D, Richardson K, Crutzen P, Foley JA (2009) A safe operating space for humanity. Nature 461:472–475

Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA (2003) Fingerprints of global warming on wild animals and plants. Nature 421:57–60

Rosenzweig C, Karoly D, Vicarelli M, Neofotis P, Wu QG, Casassa G, Menzel A, Root TL, Estrella N, Seguin B, Tryjanowski P, Liu CZ, Rawlins S, Imeson A, (2008) Attributing physical and biological impacts to anthropogenic climate change. Nature 453:353–358

Rowntree PR, Balton JA (1983) Simulation of the atmospheric response to soil moisture anomalies over Europe. Q J R Meteorol Soc 109:501–526

Safranyik L, Wilson WR (2006) The mountain pine beetle: a synthesis of biology, management, and impacts on lodgepole pine. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria. http://mpb.cfs.nrcan.gc.ca/synthesis_e.html. Accessed September 2010

Sandia National Laboratory (2007) Energy water roadmap report. http://www.sandia.gov/energy-water/roadmap_report.htm. Accessed December 2010

Scarre C (2009) The human past: world prehistory and the development of human societies, 2nd edn. Thames and Hudson, London

Shukla J, Mintz Y (1982) Influence of land surface evapotranspiration on the Earth's climate. Science 215(4539):1498–1501

Sinervo B, Mendez-de-la-Cruz F, Miles DB, Heulin B, Bastiaans E, Cruz MVS, Lara-Resendiz R, Martinez-Mendez N, Calderon-Espinosa ML, Meza- Lazaro RN, Gadsden H, Avila LJ, Morando M, De la Riva IJ, Sepulveda PV, Rocha CFD, Ibarguengoytia N, Puntriano CA, Massot M, Lepetz V, Oksanen TA, Chapple DG, Bauer AM, Branch, WR, Clobert J, Sites JW (2010) Erosion of lizard diversity by climate change and altered thermal niches. Science 328:894–899

Sivakumar MVK, Stefanski R (2007) Climate and land degradation—an overview. In: Climate and land degradation. Springer, New York, pp 105–135

Small C, Nicholls RJ (2003) A global analysis of human settlement in coastal zones. J Coast Res 19:584–599

Sohl TL, Loveland TR, Sleeter BM, Sayler KL, Barnes CA (2010) Addressing foundational elements of regional land-use change forecasting. Landscape Ecol 25:233–247

Sun G, McNulty SG, Myers JAM, Cohen EC (2008) Impacts of multiple stresses on water demand and supply across the southeastern United States. J Am Water Resour Assoc 44:1441–1457

Termorshuizen JW, Opdam P (2009) Landscape services as a bridge between landscape ecology and sustainable development. Landscape Ecol 24:1037–1052

US Department of Commerce (2011) Trends in atmospheric carbon dioxide. Earth Systems Research Laboratory, National Oceanographic and Atmospheric Administration. http://www.esrl.noaa.gov/gmd/ccgg/trends/. Accessed February 2011

USAID (U.S. Agency for International Development) (2009) LAC tropical forest and biodiversity FAA 118/119 country analyses. U.S. Agency of International Development, Washington, DC. http://www.usaid.gov/locations/latin_america_caribbean/environment/118_119.html. Accessed September 2010

van der Werf GR, Morton DC, DeFries RS, Olivier JGJ, Kasibhatla PS, Jackson RB, Collatz GJ, Randerson JT (2009) CO_2 emissions from forest loss. Nat Geosci 2:737–738

Van Doorn AM, Bakker MM (2007) The destination of arable land in a marginal agricultural landscape in South Portugal: an exploration of land use change determinants. Landscape Ecol 22:1073–1087

Vicuna S, Leonardson R, Hanemann MW, Dale LL, Dracup JA (2008) Climate change impacts on high elevation hydropower generation in California's Sierra Nevada: a case study in the Upper American River. Clim Chang 87(Suppl 1):S123–S137

Viña A, Echavarria FR, Rundquist DC (2004) Satellite change detection analysis of deforestation rates and patterns along the Colombia–Ecuador border. Ambio 33:118–125

Walter KM, Zimov SA, Chanton JP, Verbyla D, Chapin FS (2006) Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. Nature 443(7107): 71–75

Weishampel JF, Knox RG, Levine ER (1999) Soil saturation effects on forest dynamics: scaling across a southern boreal/northern hardwood landscape. Landscape Ecol 14:121–135

Werth D, Avissar R (2002) The local and global effects of Amazon deforestation. J Geophys Res 197:8087

Wickham JD, Riitters KH, Wade TG, Coan M, Homer C (2007) The effect of Appalachian mountaintop mining on interior forest. Landscape Ecol 22:179–187

Wilbanks TJ, Bhatt V, Bilello DE, Bull SR, Ekmann J, Horak WC, Huang YJ, Levine MD, Sale MJ, Schmalzer DK, Scott MJ (2007) Effects of climate change on energy production and use in the United States. Department of Energy, Office of Biological & Environmental Research, Washington, DC. http://www.climatescience.gov/Library/sap/sap4-5/final-report/default.htm. Accessed March 2011

Wind BD, Wallender WW (1997) Fossil-fuel carbon emission control in irrigated maize production. Energy 22:827–846

Woodwell GM, Houghton RA (1977) Biotic influences on the world carbon budget. In: Strumm W (ed) Global chemical cycles and their alterations by man. Dahlem Knoferenzen, Berlin, pp 61–72

World Energy Council (2010) 2010 Survey of energy resources executive summary. World Energy Council, London. http://www.worldenergy.org/publications/3040.asp. Accessed April 2011

Wu J (2008) Making the case for landscape ecology: an effective approach to urban sustainability. Landsc J 27:41–50