

REVIEW SUMMARY

SUSTAINABILITY

Systems integration for global sustainability

Jianguo Liu,* Harold Mooney, Vanessa Hull, Steven J. Davis, Joanne Gaskell, Thomas Hertel, Jane Lubchenco, Karen C. Seto, Peter Gleick, Claire Kremen, Shuxin Li

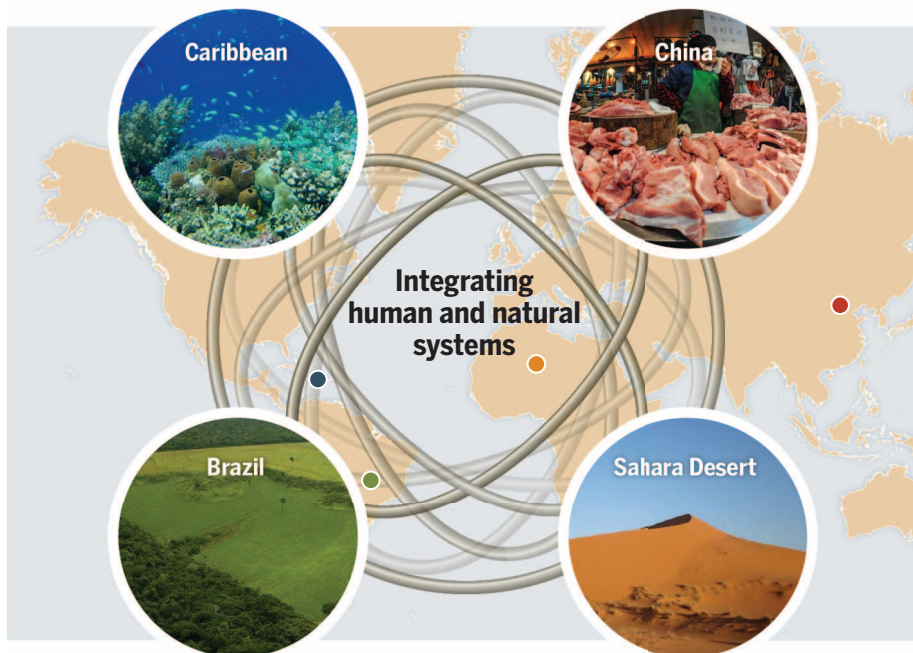
BACKGROUND: Many key global sustainability challenges are closely intertwined (examples are provided in the figure). These challenges include air pollution, biodiversity loss, climate change, energy and food security, disease spread, species invasion, and water shortages and pollution. They are interconnected across three dimensions (organizational levels, space, and time) but are often separately studied and managed. Systems integration—holistic approaches to integrating various components of coupled

human and natural systems (for example, social-ecological systems and human-environment systems) across all dimensions—is necessary to address complex interconnections and identify effective solutions to sustainability challenges.

ADVANCES: One major advance has been recognizing Earth as a large, coupled human and natural system consisting of many smaller coupled systems linked through flows of information, matter, and energy and evol-

ing through time as a set of interconnected complex adaptive systems. A number of influential integrated frameworks (such as ecosystem services, environmental footprints, human-nature nexus, planetary boundaries, and telecoupling) and tools for systems integration have been developed and tested through interdisciplinary and transdisciplinary inquiries. Systems integration has led to fundamental discoveries and sustainability actions that are not possible by using conventional disciplinary, reductionist, and compartmentalized approaches. These include findings on emergent properties and complexity; interconnections among multiple key issues (such as air, climate, energy, food, land, and water); assessment of multiple, often conflicting, objectives; and synergistic interactions in which, for example, economic efficiency can be enhanced while environmental impacts are mitigated. In addition, systems integration allows for clarification and reassignment of environmental responsibilities (for example, among producers, consumers, and traders); mediation of trade-offs and enhancement of synergies; reduction of conflicts; and design of harmonious conservation and development policies and practices.

OUTLOOK: Although some studies have recognized spillover effects (effects spilling over from interactions among other systems) or spatial externalities, there is a need to simultaneously consider socioeconomic and environmental effects rather than considering them separately. Furthermore, identifying causes, agents, and flows behind the spillover effects can help us to understand better and hence manage the effects across multiple systems and scales. Integrating spillover systems with sending and receiving systems through network analysis and other advanced analytical methods can uncover hidden interrelationships and lead to important insights. Human-nature feedbacks, including spatial feedbacks (such as those among sending, receiving, and spillover systems), are the core elements of coupled systems and thus are likely to play important roles in global sustainability. Systems integration for global sustainability is poised for more rapid development, and transformative changes aimed at connecting disciplinary silos are needed to sustain an increasingly telecoupled world. ■



Illustrative representation of systems integration. Among Brazil, China, the Caribbean, and the Sahara Desert in Africa, there are complex human-nature interactions across space, time, and organizational levels. Deforestation in Brazil due to soybean production provides food for people and livestock in China. Food trade between Brazil and China also contributes to changes in the global food market, which affects other areas around the world, including the Caribbean and Africa, that also engage in trade with China and Brazil. Dust particles from the Sahara Desert in Africa—aggravated by agricultural practices—travel via the air to the Caribbean, where they contribute to the decline in coral reefs and soil fertility and increase asthma rates. These in turn affect China and Brazil, which have both invested heavily in Caribbean tourism, infrastructure, and transportation. Nutrient-rich dust from Africa also reaches Brazil, where it improves forest productivity. [Photo credits clockwise from right top photo: Caitlin Jacobs, Brandon Prince, Rhett Butler, and David Burdick, used with permission]

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REVIEW

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Systems integration for global sustainability

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Global sustainability challenges, from maintaining biodiversity to providing clean air and water, are closely interconnected yet often separately studied and managed. Systems integration—holistic approaches to integrating various components of coupled human and natural systems—is critical to understand socioeconomic and environmental interconnections and to create sustainability solutions. Recent advances include the development and quantification of integrated frameworks that incorporate ecosystem services, environmental footprints, planetary boundaries, human-nature nexuses, and telecoupling. Although systems integration has led to fundamental discoveries and practical applications, further efforts are needed to incorporate more human and natural components simultaneously, quantify spillover systems and feedbacks, integrate multiple spatial and temporal scales, develop new tools, and translate findings into policy and practice. Such efforts can help address important knowledge gaps, link seemingly unconnected challenges, and inform policy and management decisions.

The goal of achieving global sustainability is to meet society's current needs by using Earth's natural resources without compromising the needs of future generations (1). Yet, many disparate research and management efforts are uncoordinated and unintentionally counterproductive toward global sustainability because a reductionist focus on individual components of an integrated global system can overlook critical interactions across system components. Although our planet is a single system comprising complex interactions between humans and nature, research and management typically isolate system components (such as air, biodiversity, energy, food, land, water, and people). As a result, the compounding environmental impacts of human activities have too often been missed because they go beyond the organizational level, space, and time of focus. For example, large amounts of affordable and reliable energy are available in fossil fuels, but concomitant emissions of carbon dioxide (CO₂) will alter global climate and affect other human and natural systems—a trade-off that current policies have not adequately addressed (2). Likewise, attention to growing more food on

land may inadvertently result in excess use of fertilizers and in turn eutrophication of downstream coastal waters that compromises food production from the ocean. Progressing toward global sustainability requires a systems approach to integrate various socioeconomic and environmental components that interact across organizational levels, space, and time (3–5).

Systems integration generates many benefits compared with isolated studies, including understanding of interconnectivity and complexity (Table 1). Here, we review recent advances in developing and quantifying frameworks for systems integration of coupled human and natural systems; illustrate successful applications, focusing on unexpected impacts of biofuels and hidden roles of virtual water and discuss future directions for using systems integration toward global sustainability.

Framework development and quantification

The development and quantification of frameworks are critical steps in integrating human and natural systems (6–9). For instance, interactions between sectors and stakeholders in the human system or between biotic and abiotic factors in the natural system at different organizational levels (for example, government agencies from local to national levels, and food trophic levels from producers to consumers in ecosystems) lead to emergent properties that individual components do not have (10). All coupled systems evolve over time as complex adaptive systems (11). Their interactions, emergence, evolution, and adaptation also vary with spatial scales (12). Accordingly, integration along organizational, spa-

tial, and temporal dimensions is needed to avoid sustainability solutions in one system that cause deleterious effects in other systems. Such integration can also enhance positive and reduce negative socioeconomic and environmental effects across multiple systems at various organizational levels over time (Table 1).

Integration requires blending and distilling of ideas, concepts, and theories from multiple natural and social science disciplines as well as engineering and medical sciences (4, 13), various tools and approaches (such as simulation, remote sensing, and life cycle assessment), and different types and sources of biophysical and socioeconomic data (14). For example, integrated assessment models such as those used by the Intergovernmental Panel on Climate Change (IPCC) analyze information from diverse fields to understand complex environmental problems (such as acid rain, climate change, energy shortages, and water scarcity) (15, 16). The Global Trade Analysis Project has recently evolved from a database for analyzing global trade-related economic issues to a platform for integrating trade with global land use and associated greenhouse gas (GHG) emissions (17). The Global Biosphere Management Model analyzes and plans land use among sectors (agriculture, forestry, and bioenergy) across the globe in an integrated way (18). Below, we illustrate the development and quantification of some important integration frameworks that have led to substantial advances.

Ecosystems services, environmental footprints, and planetary boundaries

Human and natural systems interact in a multitude of ways. Several integration frameworks bring multiple aspects of human-nature interactions together (Fig. 1). Quantifying the services that ecosystems provide (Fig. 1A) for societal needs (such as clean water, nutrient cycling, and recreation) (6) helps assign value to natural components for humans. Recent advances consider a variety of ecosystem services simultaneously in order to evaluate trade-offs and synergies among them (19). Environmental footprint (20) and planetary boundary (21) frameworks attempt to quantify the negative effects that human activities have on natural systems. The environmental footprints framework quantifies resources (such as natural capital) consumed and wastes generated by humans (Fig. 1B) (20). Recent manifestations of the concept go beyond the previously developed ecological footprints framework by including more diverse types of footprints [for example, water, carbon, and material footprints (20)]. Planetary boundaries are threshold levels for key Earth system components and processes (such as stratospheric ozone, global freshwater, and nitrogen cycling) beyond which humanity cannot safely be sustained (21) (Fig. 1C).

Quantifying the above frameworks relies on systems integration. For instance, organizational integration in environmental footprint analysis demonstrates how different human activities contribute to human impacts at local to global levels (20). Spatial integration is illustrated in integrated

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Table 1. Example benefits of systems integration.

Benefit	Illustrative study
Revealing mechanisms of ecological degradation in protected areas Understanding complexity	Socioeconomic factors (such as forest harvesting, fuelwood collection, and increases in household numbers) are responsible for ecological degradation in protected areas for giant pandas (which are supposed to be protected from human activities) (100). Agricultural intensification schemes may promote further agricultural expansion over the long term; responses varied across space and were nonlinearly related to agricultural inputs (101).
Improving economic efficiency	Integrated assessment modeling shows specific cost estimates for delaying climate change mitigation with respect to geophysical, technological, social, and political factors (102).
Reducing environmental impacts in distant places	Integrated cross-boundary management suggests ways of decreasing the spread of pollution and spillover of climate-change effects to distant places around the globe (15).
Addressing multiple issues simultaneously	The climate change–health–food security nexus demonstrates ways that management measures can improve all three key issues at the same time (103).
Assessing the feasibility of multiple and conflicting goals	Integrated coastal zone management allows for multiorganizational management for competing interests such as recreation, fisheries, and biodiversity conservation (104).
Developing priorities for research and sustainability action	Integrated modeling of global water, agriculture, and climate change pinpoints areas vulnerable to future water scarcity and puts forth actionable strategies for mitigation (16).
Identifying complementary conservation and management strategies	Coupling global energy security policy with climate change and air pollution policies (the air-climate-energy nexus) would decrease oil consumption compared to implementing energy policy alone (46).
Enhancing synergies among factors	Cross-site integration of natural resource management approaches in response to disturbances shows opportunities for reframing ecosystem management to enhance collaboration among institutions (such as NGOs, government agencies, research organizations, businesses) (105).
Anticipating feedbacks	A lag between fire control management and the response of the forests to such changes affects the eagerness of landowners to continue implementing control measures (106).
Detecting latencies	The latent effect of mosquito ditch construction on fish populations only emerged during new pressures from residential development and recreational fisheries (107).
Maximizing economic gains and minimizing environmental costs	Integrated soil-crop management system could maximize grain yields, while minimizing applications of fertilizers and GHG emissions (108).

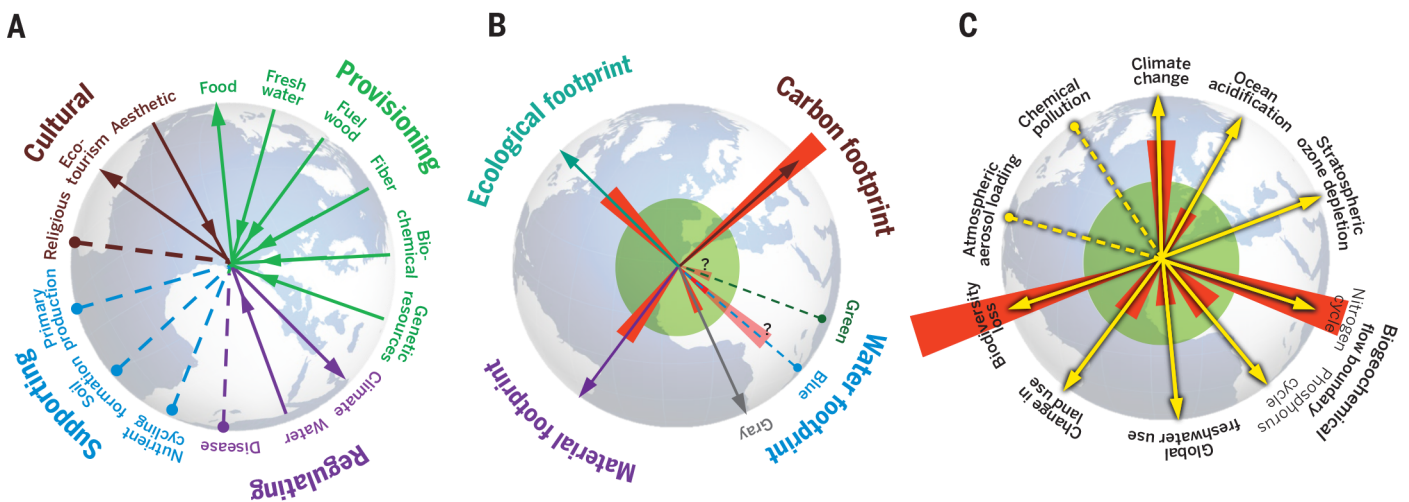


Fig. 1. Examples of ecosystem services, environmental footprints, and planetary boundaries. (A) Ecosystem services. (B) Environmental footprints. (C) Planetary boundaries. Outward arrows in (A to C) indicate increases in the values, inward arrows indicate decreases, and dashed lines indicate no data. In (B) and (C), the inner green shading represents maximum sustainable footprints (20) and safe operating space for nine planetary system variables (21), respectively. Red wedges refer to the estimated current positions for the variables. Most of the ecosystem services in (A) decreased between the 1950s to early 2000s (94). In (B), at least three types of footprints (eco-

logical, carbon, and material) have exceeded maximum sustainable footprints (20). Blue water footprint was 1690 billion m³/year (1985–1999) (81), gray water footprint increased during 1970–2000 (95), and green water footprint is 6700 billion m³/year (without reference point) (20). Question marks indicate that the information is uncertain. Carbon footprint increased during 1960–2009 (96). With every 10% increase in gross domestic product, the average national material footprint increases by 6% (97). For (C), all planetary system variables have increased in values between preindustry and 2000s, and three boundaries have been crossed (21).

landscape planning for ecosystem services, which allows for coordination across space. For example, it can promote afforestation and reforestation in upland areas above irrigated agricultural systems, thus reducing erosion, protecting waterways, minimizing flooding, providing drinking water, and facilitating sustainable agricultural production (22). Temporal integration is crucial to quantify the planetary boundaries framework, as short-term fluctuations in key Earth system processes are scaled up to predict long-term trends, many of which cannot be accurately predicted without a systems approach (21). Temporal integration can also reveal legacy effects of prior human-nature couplings. For example, carbon footprints are driven in large part by past land use (23). A condition termed “carbon lock-in” has been used to describe systems that have evolved over long time frames to become dependent on fossil fuels (24, 25). The fossil energy system is comprised of long-lived infrastructure such as power plants, which represent an investment in future CO₂ emissions. Retiring this infrastructure before the end of its economic or physical lifetime would entail substantial costs. As of 2013, it is estimated the global committed emissions related to existing fossil infrastructure are roughly 700 billion tons of CO₂ (26).

Human-nature nexuses

In contrast to the conventional decision-making that takes place within separate disciplines or sectors, the human-nature nexus framework recognizes the interdependency between two or more issues (or nodes) and addresses them together. For example, the energy-food nexus considers both the effects of energy on food production, processing, transporting, and consumption, and the effects of food (such as corn) production on the generation of energy (such as ethanol) (27).

The nexus framework can help anticipate otherwise unforeseen consequences, evaluate trade-offs, produce co-benefits, and allow the different and often competing interests to seek a common ground (28) and co-optimization (29). The vast majority of the 229 human-nature nexus studies recorded in the Web of Science (as of 16 August 2014) analyzed two-node nexuses (80%), with only 16 and 4% of the nexus studies including three and four nodes, respectively. Although the concept of food-energy nexus first appeared in 1982, there was no paper recorded in the Web of Science for many years. The interest in the nexus framework has reemerged recently and has grown rapidly since 2010. Several two-node nexuses have received special focus, including energy-water nexus, food-water nexus, energy-food nexus, air-climate nexus, health-water nexus, and energy-national security nexus. Among the more commonly examined three- and four-node nexuses are economy-environment-land nexus and climate-energy-food-water nexus. Adding more nodes to a nexus framework leads to more complexity but also captures greater reality. For instance, the climate-energy-food nexus considers not only the interrelationships between energy and food, but also the relationships between energy and climate (for example,

energy use emits CO₂, and climate change affects energy demand such as heating and cooling) and interrelationships between food and climate (for example, climate changes affect food production, and CO₂ is emitted throughout the food production, processing, transporting, and consumption).

The nodes in the nexus framework are mediated by and influence many organizational levels. For example, energy production and use are shaped by international markets and policies at different government organizations and at the same time influence many trophic levels of animals, plants, and microorganisms (30). Building on the increasing recognition of conceptual interconnections among various nodes, efforts are under way to quantify their relationships, such as via hydro-economic modeling (31), structural and nonstructural economic models (32), and life cycle assessments (33). Scenario analysis is particularly promising for teasing out roles of different organizations functioning at different scales (34, 35). For example, the Agrimonde model has been used to examine intersections between food and numerous other sectors (including energy and water) worldwide under different growth and consumption scenarios (35) and illustrates the effects of diverse individual governments on global cross-sector dynamics.

Temporal integration is also a key element of the nexus framework. For example, recent long-term quantitative integration studies on the economy-energy nexus show that reductions in energy use can have negative impacts on gross domestic product (GDP) in the short-term but little detectable effect over the long term (36). Alternatively, one model predicted that a small increase in foreign trade in Indonesia will lead to substantial increases in long-term per capita CO₂ emissions, although its contribution to CO₂ emissions is negligible in the short term (37).

Telecoupling

Many studies on sustainability have been place-based even if they look at coupled systems [for example, the energy-water nexus in the United States (38)]. However, economic production and resource use in different regions or countries may lead to very different consequences. Furthermore, there are increasing distant interactions around the world so that local events have consequences globally (39). For example, each year several hundred million tons of dust from Africa (especially the Sahara desert) travel via the air across the Atlantic Ocean to distant places such as the Caribbean, where it causes severe impacts, including decline in coral reefs, increase in asthma, disease spread, and loss of soil fertility (40, 41). Greenhouse gases emitted into the atmosphere from a point source become mixed and transported globally, affecting societies and ecosystems far distant from the point sources of origin. Many of the changes to the biotic composition of local places can also affect society regionally and globally through ever-increasing global trade as well as the often dramatic impact of invasive species and disease transmission. In other words, patterns and processes at one place may enhance or

compromise sustainability in other places (42). Human actions [such as production of biofuels (43)] in one place may create unintended consequences elsewhere [such as carbon leakage (44), biodiversity losses (45, 46), and pollution (47)]. Although external factors originating from other systems are sometimes considered in sustainability research and practices, they are typically treated as one-way drivers of changes in the system of interest, with little attention to the feedbacks between the system of interest and other systems (6, 42).

The framework of telecoupling (socioeconomic and environmental interactions over distances) has been developed to tie distant places together (42). It is a natural extension of the frameworks of coupled human and natural systems and built on disciplinary frameworks such as climate teleconnections (distant interactions between climate systems), urban land teleconnections (land changes that are linked to underlying urbanization dynamics) (7), and economic globalization (distant interactions between human systems). So far, the telecoupling framework has been applied to a number of important issues across spatial scales, such as global land-use and land-change science (39, 48, 49), international land deals (39), species invasion (39, 42), payments for ecosystem services programs (50), and trade of food (42) and forest products (9).

The framework is particularly effective for understanding socioeconomic and environmental interactions at international scales. For example, the flow of coal from Australia (sending system) to a number of countries and regions (receiving systems; for example, Japan, the European Union, and Brazil) reflects abundant Australian coal supplies and the demand for coal in receiving systems (Fig. 2). The coal trade is facilitated by many agents in receiving and sending systems (such as government agencies that make coal trade policies) and international organizations (such as shipping companies). Many other countries (such as those in Africa) are spillover systems—systems that may be affected by the coal flows because of financial flows between sending and receiving systems as well as the CO₂ emissions produced when the coal is burned. Global efforts to address this and similar feedbacks, such as the REDD+ program to mitigate CO₂ emissions from deforestation (51) and the Green Climate Fund to facilitate low-emission projects in developing nations (52), should focus on all countries.

The telecoupling framework can also be useful at regional or national scales. For example, the 20 million residents in China’s capital city of Beijing (receiving system) receive clean water from the Miyun Reservoir watershed (sending system), more than 100 km away from the city (50). The framework explicitly links agents, causes, and effects in the sending and receiving systems. For instance, the quantity and quality of the water flows are made possible through the Paddy Land-to-Dry Land program, an ecosystem services payment program that Beijing established with the farmers in the watershed who converted rice cultivation in paddy land to corn production

in dry land to provide clean water for Beijing in exchange for cash payments (53). Through systematic analysis, the framework also helps identify research and governance gaps, such as spillover systems—regions that are affected by water and cash flows between the watershed and Beijing but have received little attention from researchers and government agencies (50).

The telecoupling framework also emphasizes temporal dynamics. A lack of temporal integration may miss key dynamics and create a misunderstanding of infrequent but drastic changes, such as disasters, wars, outbreaks of deadly diseases such as Ebola (54), regime shifts, and profound policy changes. For instance, in the Wolong Nature Reserve of China designated for conserving the endangered giant pandas, the devastating earthquake in 2008 substantially altered the telecouplings between Wolong and outside systems [for example, collapse of tourism and agricultural trade (55)]. Studies omitting the earthquake impacts could misrepresent the mechanisms behind the system dynamics (such as increases in landslides and relocation of households).

Applications of systems integration

Systems integration has been applied successfully to many sustainability issues. Integrated Coastal Zone Management (56), Marine Spatial Planning (57), and Ecosystem-Based Management (58) all integrate multiple dimensions for natural resource management. Although some of these practices have existed for several decades, there have been continued efforts for more integration, new advances, and novel insights. For example, Ecosystem-Based Management has expanded to tackle issues not traditionally thought of within

natural resource management, such as food security (59), politics (60), and disease (61). The examples of biofuels and virtual water below also illustrate the importance of systems integration in detail. We chose to focus on these two examples because they are emerging and contentious global phenomena that represent challenging sustainability issues, and they have unexpected and hidden socioeconomic and environmental effects that were impossible to reveal without systems integration.

Unexpected impacts of biofuels

The environmental and socioeconomic impacts of biofuels have been among the most hotly contested policy issues over the past decade. The United States, European Union, and nearly three dozen other countries in Africa, Asia, and the Americas have developed biofuel mandates or targets (62). This enthusiasm was buoyed by the prospect of displacing high-priced oil imports, generating rural incomes, and contributing to climate change mitigation. As of 2006, it was suggested that biofuels could be both economically and environmentally beneficial. However, with the implementations of these policies and systems integration research, serious concerns have arisen about their geospatial impacts and the temporal viability of these mandates.

Biofuels are a prime topic for systems integration research because biofuel production and consumption as well as their impacts vary across time, space, and organizational levels. For instance, the carbon fluxes after conversion of new croplands depend not only on below- and above-ground carbon at present, but also on the legacy effects stemming from historical land use such as

land clearing as well as subsequent cultivation and cropping practices (63). The United States and Brazil were responsible for 90% of the global biofuel production of 105 billion liters in 2011, but several other countries with new mandates such as China, Canada, and Argentina are increasing the spatial extent of production (64). Assessing organizational impacts on biofuel production encompasses analysis that integrates across institutions. For example, when and where additional cropland is converted for biofuel production depends critically on local, national, and international institutions, as well as the global supply chain.

The systems integration frameworks discussed above have direct relevance to biofuels. For example, the environmental footprint framework has been applied to assess the impacts of biofuels. It is estimated that the global footprint from biofuels was ~0.72 billion gha in 2010 and expected to rise by 73% in 2019 (consisting of land use, carbon, embodied energy, materials and waste, transport, and water) (65). From the perspective of ecosystem services, biofuels have both positive (for example, energy) and negative (for example, loss of food and freshwater services) impacts. Biofuel production also affects several planetary boundaries, including climate change, land-use change (proportion of cropland), nutrient cycles (increased use of phosphorus and nitrogen), and biodiversity loss (66). For instance, it is estimated that corn-based ethanol nearly doubles greenhouse emissions across the world over a 30-year period because of land-use change (43).

Biofuels have also been studied under the human-nature nexus framework—in particular, the energy-food nexus and energy-food-water nexus. Rising demand for ethanol feedstocks bid

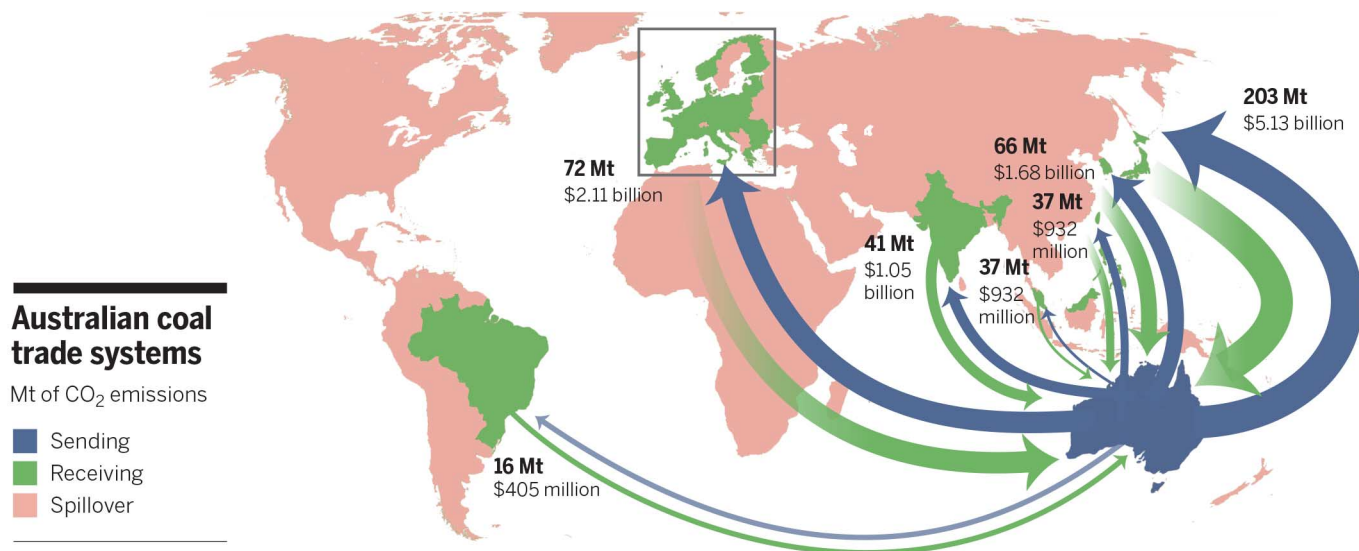


Fig. 2. Illustrative example of sending, receiving, and spillover systems, as well as flows under the telecoupling framework. In the case of trade in Australian coal in 2004 [measured in megatons (Mt) of CO₂ emissions], Australia is a sending system (in blue), the main receiving systems are in green (destinations of the coal are Japan, South Korea, Taiwan, Malaysia, India, the European Union, and Brazil), and the spillover systems are in light red (all other countries and regions are affected by CO₂ emissions from

using the coal produced in Australia and consumed in the receiving systems). The arrows show the magnitude of the flows. Countries that receive less than 10 Mt of emissions of Australian coal are not included. Flows to Europe are aggregated to include all 28 member states of the European Union [data from (44)]. Financial flows take place between sending and receiving systems but may also affect financial conditions in spillover systems indirectly [data from (98)].

up food price (67), which has major implications for food security (68). And, questions have been raised about the adverse interplay between biofuel mandates and increased interannual variability in crop production anticipated under future climate change (69). Water also comes into play, as limits on the future availability of water for irrigated agriculture will shift the location of cropland conversion owing to biofuel expansion toward regions with carbon-rich rainfed agriculture. Overall, accounting for hydrological constraints boosts estimated GHG emissions from land use by 25% (70).

Telecoupled processes such as international trade and flows of information (for example, global market prices) cause biofuel programs in one part of the world to translate spatially into land conversion in other regions (indirect land use). They have already contributed to cropland expansion in the United States and overseas and to cascading and spillover effects over long distances (Fig. 3). National biofuel programs, which looked environmentally beneficial at first

blush, might in fact lead to increased environmental damage when viewed over time and at the global scale (42, 71). Unlike early analyses (42) that assumed that higher prices effectively influenced all agents in the market equally, subsequent research has revealed that some agricultural suppliers (such as the United States and Argentina) are more closely telecoupled than others (72). The spatial pattern and extent of land conversion stemming from biofuels are also affected by geophysical characteristics such as potential productivity of the newly converted lands.

Hidden roles of virtual water

Although many sustainability studies have focused on flows of real material and energy such as biofuels, there has been increasing interest in the flows of “virtual” material and energy, such as “virtual water,” “virtual energy,” “virtual land,” and “virtual nutrients” (73). Virtual resources are those resources used for production and incorporated into goods and services in the same way that related pollution and impacts are embodied

(or hidden) in these products. In the case of water, for example, it is used to grow crops, raise livestock and grow their food, and produce marketable goods. Virtual water is traded among countries as goods are traded. Globally, the volume of virtual water trade and the number of links (pairs of trading countries) have both doubled from 1986 to 2010 (74). With roughly 27 trillion m³ of water traded virtually worldwide in 2010 (74), virtual water trade from water-rich countries has helped mitigate water shortages in water-poor countries (75). The concept of virtual resources has helped analysts think more clearly about the real risks of resource scarcity and the role that trade plays in mitigating or worsening those risks (76, 77). Targeted trade policies may help to further prevent water scarcity by encouraging more water-efficient trade links (78).

Virtual water is a good target for systems integration research because the issues involved are dynamic across time, space, and organizational levels. Global water scarcity issues are inherently temporally sensitive, with cumulative effects

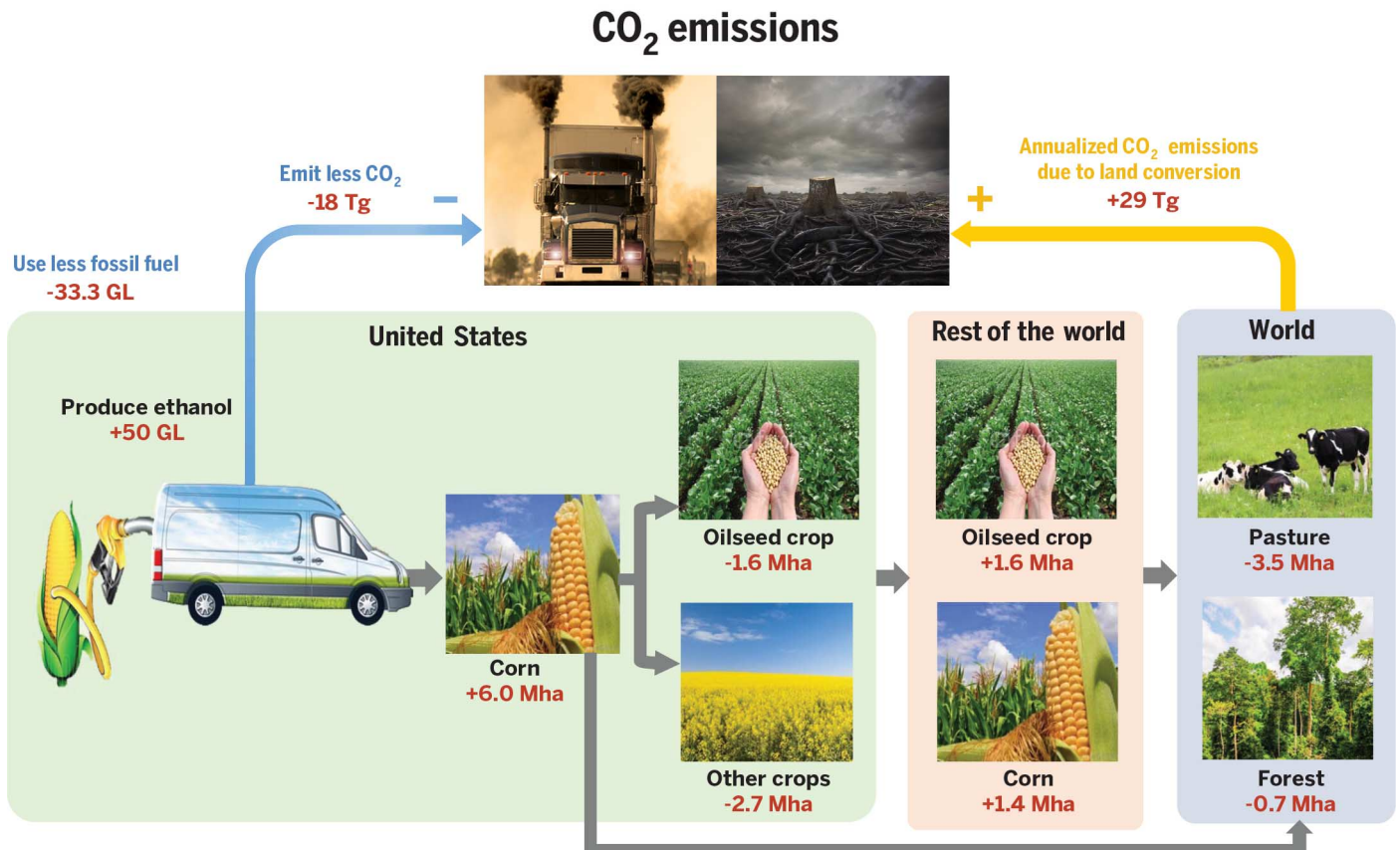


Fig. 3. Cascading and spillover effects of biofuel production on land conversion and CO₂ emissions, as revealed by systems integration.

Meeting the Renewable Fuel Standard mandate [to produce 50 Ggal (GL) of additional ethanol on top of the 2001 production level] in the United States reduces the use of petroleum but requires additional corn area (99). The expansion in U.S. corn area leads to reduction in harvested area of oilseeds and other crops in the United States. This boosts world prices for these crops and encourages more production of oilseeds and corn in the rest of the world. The expansion of cropland in the United States and the rest of the world leads to

more emissions of CO₂ and the conversion of pasture and forest lands around the world. This land conversion also releases CO₂, offsetting the reduction of CO₂ emissions from using less fossil fuels and more biofuels (assuming a 2/3 ethanol/petroleum energy conversion rate). Estimates are on an annual basis over a 30-year production period for the biofuel facilities and in approximate amounts derived from (99). Arrows indicate the direction of influences. Symbols “-” and “+” refer to decrease and increase, respectively, in land area, ethanol, fossil fuel, or CO₂. Tg, teragrams; Mha, million ha. [Graphics are used with permissions from Fotolia.com]

stemming from legacies of overuse of water interacting with new drivers such as climate change. Estimates suggest that global virtual water trade may decrease with climate change because of the difficulty of growing crops in warmer, drier climates [water savings from reduction in growing rice, soybeans, and wheat may amount to up to 1.5 trillion m^3 in 2030 (78)]. Also, there was a profound shift in the spatial distribution of human populations (thus, water demand) relative to water distribution over the past few decades. In 1986, 68% of the world's population was in water-exporting countries, but by 2010, the distribution was almost completely reversed, with 60% of the global population in water-importing countries (74). One of the greatest organizational concerns related to virtual water is that a few countries control the majority of the global trade, which leaves the market vulnerable to the decisions made by a few key players (74). In addition, there is unequal distribution of resources within countries and a tendency for local agrarian communities to be marginalized owing to trade dictated by country-level agencies (79).

The ecosystem services framework has contributed to virtual water research in many ways. For example, Canada is a major exporter of virtual water worldwide (95 Gm^3 /year); exporting virtual water affects the ecosystem services provided by the nation's boreal forests, which make up nearly 60% of Canada's territory (80). Production of commodities through processes such as hydroelectric power generation, oil extraction, crop irrigation, and livestock-rearing contributes to virtual water exports, which in turn threaten freshwater resources that are a key part of the boreal forests. Boreal freshwater comprises 80 to 90% of Canada's lakes and 25% of the entire Earth's wetlands (80). Removal of water compromises the estimated annual gain of \$703 billion in ecosystem services that the boreal forests pro-

vide, including carbon storage, flood control and water filtering, biodiversity conservation, and pest control (80).

The environmental footprints framework has informed virtual water research by depicting the water resources used for production of goods and services ("water footprints"). For example, 2,320 Gm^3 /year of the total global water footprint of 9087 Gm^3 /year comes from virtual water trade (81). There is a close relationship between virtual water and planetary boundaries because one of the nine key planetary boundaries identified is the limit to global freshwater use (21). A related concept—"peak water"—helps to illustrate how close global freshwater bodies are to this threshold. Global water consumption has already reached a peak and begun to decline in many areas because of limited remaining water (13). Furthermore, scarcity in global freshwater is in large part linked to the virtual water embedded in agricultural production and trade (81). The human-nature nexus framework is also useful for virtual water research. For example, a study on water-food nexus indicates that 76% of virtual water trade is attributed to crops or crop-derived products (81).

Virtual water trade varies spatially and is an important telecoupling process. The main virtual water exporters (sending systems) are water-rich regions in North and South America and Australia, whereas Mexico, Japan, China, and water-poor regions in Europe are the main importers (receiving systems) (Fig. 4) (75). Sending and receiving systems involved in virtual water trade have dynamic roles. Asia recently switched its virtual water imports from North America to South America (82). On the other hand, North America has engaged in an increased diversification of intraregional water trade while trading with distant countries in Asia (82). China has undergone a dramatic increase in virtual water

imports since 2000, via products such as soybeans from Brazil (nearly doubling from 2001 to 2007 and amounting to 13% of the total global world water trade) (82). The spatial shift in the use of soybean products in Brazil from domestic to international has led to water savings in other countries, but at the cost of deforestation in Brazilian Amazon (82). Within-country virtual water transfer is also common. For example, virtual water flow through grain trade from North China to South China goes in the opposite direction of real water transfer through large projects, such as the South-to-North Water Transfer Project, that aim to alleviate water shortages in North China.

Future directions

Despite the substantial progress in systems integration illustrated above, many important challenges remain. For example, the integrated frameworks have been studied largely in isolation, although they are interconnected through human activities (for example, using more ecosystem services may lead to larger environmental footprints). Achieving a greater degree of integration would involve analyzing and managing coupled human and natural systems over longer time periods, larger spatial extents (for example, macrosystems and ultimately the entire planet), and across more diverse organizations at different levels. Below, we suggest several ways to advance systems integration with the intent of improving its theoretical foundations, expanding its tool box, and providing broad implications for management and policy.

Incorporate more human and natural components simultaneously

Although some previous studies have considered multiple components of coupled human and natural systems, many components are either not

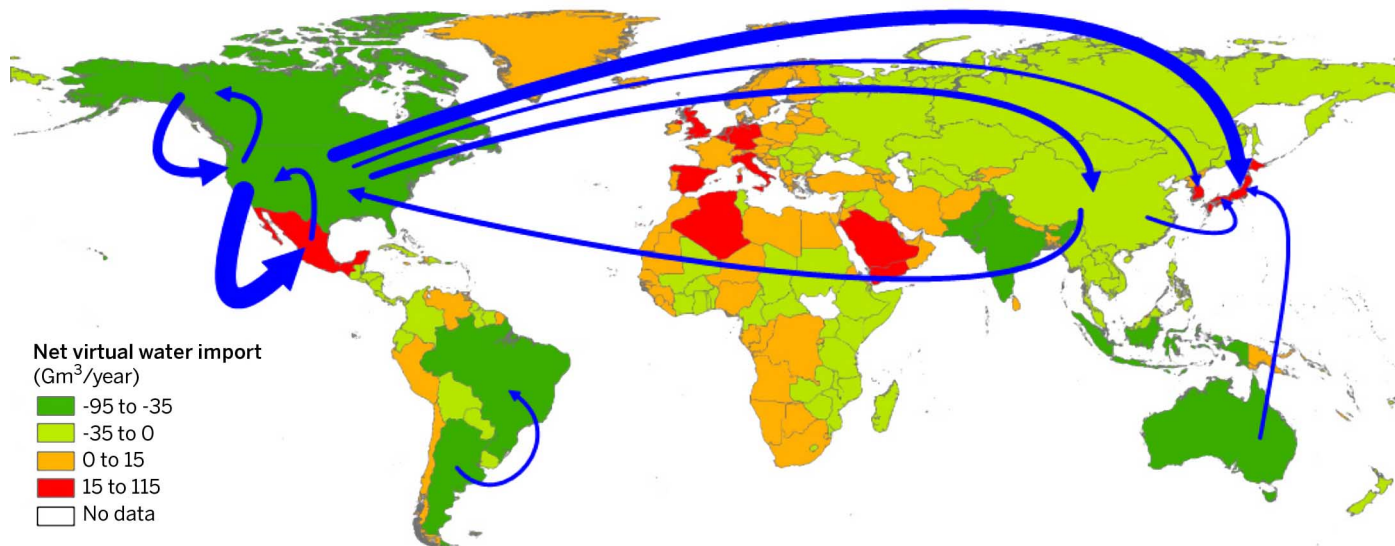


Fig. 4. Balance and flows of virtual water related to trade of agricultural and industrial products during 1996–2005. Net exporters (sending systems) are in green, and net importers (receiving systems) are in red. The arrows indicate the relative sizes of large gross virtual water flows between sending and receiving systems ($> 15 \text{ Gm}^3$ /year). Countries without arrows are potential spillover systems of the large virtual water flows. Data are from (81).

considered or treated as exogenous variables, leading to biases and even incorrect conclusions. For example, a food-water nexus study without considering GHG emissions during groundwater extraction for irrigation of crops in China underestimated GHG emissions by as much as 33.1 MtCO₂e (83). One way to correct this problem is to convert more variables from exogenous to endogenous—internalize all important relevant variables—so that their dynamics and feedback effects are explicitly studied. For instance, considering multiple telecoupling processes (such as species invasion, trade, disease spread, and technology transfers) at the same time can help link many seemingly disconnected, distant interactions. Unifying evolutionary approaches such as seen with complex adaptive systems (84) may provide productive ways to integrate disparate ideas and understand temporal dynamics and sustainability of coupled systems.

Identify and quantify spillover systems

Previous research on issues such as trade often focused on sending and receiving systems (for example, trade partners), with little attention to spillover systems (for example, nontrade partners)—other systems affected by the interactions between sending and receiving systems. Although some previous studies have recognized some spillover effects [such as spatial externalities (85, 86)], they were often on either socioeconomic or environmental effects, rather than all effects simultaneously. Furthermore, they rarely consider other components of spillover systems (causes, agents, and flows) as articulated in the telecoupling framework (41). Identifying and quantifying other components of spillover systems related to spillover effects may help understand the mechanisms behind the spillover effects and develop more effective management strategies. Connecting spillover systems with sending and receiving systems through network analysis (87) may generate fruitful outcomes, such as the appreciation of dynamic interrelationships among different systems.

Explicitly account for feedbacks

Human-nature feedbacks are a core component of coupled systems. For instance, an important negative feedback in Wolong Nature Reserve for giant pandas in China occurred when deforestation and panda habitat degradation by local households prompted the government to develop and implement new conservation programs that provide subsidies for local households to monitor forests and thus reduce deforestation and improve panda habitat (88). This feedback has helped forest and habitat recovery while increasing income for local households. More innovative measures such as this are needed to identify and use feedbacks as mechanisms for sustainability.

Integrate multiple temporal and spatial scales

Human and natural processes and patterns at multiple scales may be different, and they can

interact with each other. For example, food production at the local scale may create jobs at the local scale but may not affect overall job creation at the global scale. Many urban sustainability efforts focus on locally specific solutions that may not be scalable (7). Thus, considering multiple spatial scales at the same time can help identify all important factors, their interdependence, and their effects and nonlinear relationships. Temporally, short-term studies should be combined with long-term studies in order to maximize the strengths of each approach. For instance, short-term studies may capture more nuanced immediate changes in system behavior, but long-term studies may account for temporal dynamics, time lags, cumulative effects, legacy effects, and other phenomena (such as rare events) that cannot be seen over shorter terms. More systematic incorporation of human dimensions to long-term studies such as the Long-term Ecological Research sites and the National Ecological Observatory Network is needed.

Develop and use new tools

More effective integration requires developing and using powerful tools to overcome difficult barriers (for example, mathematical and computational challenges, quantification of impacts at one scale on other scales, and relationships among patterns and processes across scales and across borders) and to predict emergence of unexpected threats for sustainability policy and management. Examples include spatially explicit life cycle assessment, supply chain analysis, and multilevel modeling. Agent-based models are particularly promising tools because they take interactions (such as human adaptation to environmental changes) at different scales into account and model coupled systems as complex adaptive systems. Agent-based models create virtual worlds that mimic the real world, in contrast to traditional empirical statistical models (such as econometric models) that are fitted to past data and fail when the future differs from the past, and dynamic stochastic general equilibrium models that presume a perfect world and ignore disturbances or crises (89). Many agent-based models have been developed in various disciplines to provide insights on complexities and information for policymaking in issues such as economic development and management of common spaces (90, 91). However, new models are needed to account for telecoupled systems. Also, increasing computational power will allow agent-based models to include more agents in larger areas and ultimately all important agents across the world. As more high-resolution data become available, it is necessary to develop and use big data tools (such as distributed databases, massively parallel processing, and cloud computing) for effective and efficient searching, retrieving, analysis, and integration (92).

Translate findings into policy and practice

Systems integration can provide more unbiased information for policy and practice to help clarify responsibilities, mediate trade-offs, reduce con-

licts, and anticipate future trends. It is necessary to foster coordination among multiple national and international policies and minimize situations in which different policies offset one another because of conflicting goals and counterproductive implementation. Unfortunately, institutions and regulations have traditionally focused on single issues and often do not have the mandate or infrastructure to address the organizational connections and detrimental spillovers. The World Trade Organization, for example, has the principal mandate of promoting global trade. One of the spillover effects of this mission is the global transmission of invasive species, but the means to address invasive species are weak compared with the forces driving the global market (93). Adopting the telecoupling framework can help assign responsibilities of addressing spillover effects (such as CO₂ emissions and species invasion) to consumers and producers (for example, via regulation at the source of extraction or consumption) as well as others such as traders of goods and products across space. Last, governments need to incorporate long-term studies into their policies to account for the complex dynamics of coupled systems (such as time lags). More applications of systems integration frameworks and methods such as those discussed in this paper can accelerate understanding and solving global sustainability challenges.

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