doi:10.2489/jswc.71.4.85A

FEATURE

Global food security and nexus thinking

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Major global issues of the twenty-first century (table 1), drastically impacting planetary processes and ecosystem functions, are driven by the unprecedented growth in human population and the ever-increasing affluential lifestyle. Important among these are climate change, food and nutritional insecurity, soil degradation, eutrophication and scarcity of water resources, tropical deforestation, and extinction of species. Whereas the Anthropocene began with the onset of settled agriculture about 10 millennia ago (Ruddiman 2003, 2005), its impact has been accelerated since the Industrial Revolution circa 1750 (Crutzen 2000). Thus, there is a growing emphasis on planetary stewardship (Sagan 1997) because of an increasing awareness that anthropogenic activities are driving the earth system into some irreversible changes (Steffen et al. 2011). There are indeed limits to economic growth (Meadows et al. 1972), the term "sustainable growth" is considered an oxymoron (Bartlett 1994), and realities of the Anthropocene (Steffen et al. 2007) cannot be ignored. As an industry, modern agriculture is extremely inefficient and highly flawed. It can take several times more joules of energy (from fossil fuel) to produce 1 J of food (Bartlett 2008). Most pressing global issues of the twenty-first century (table 1) have been created by inappropriate solutions to some routine concerns. Often, "the chief cause of problems is solutions" (Bartlett 1994).

Therefore, the strategy is to address global issues by following a system approach based on interdisciplinarity and interconnectivity, and identification of synergisms and ancillary benefits among components. This system approach takes into consideration all components that constitute the whole. Interdisciplinarity entails the use and integration of methods and analytical frameworks from more than one academic discipline to address an issue (e.g., climate change, soil erosion, and soil carbon [C] farming). The goal is to (a) integrate concepts and basic principles from several disciplines to systematically create a coherent framework of sustainable management of soil; (b) identify and focus on synergism among disciplines for addressing soil erosion, salinization, drought stress, nutrient depletion, acidification, loss of biodiversity, soil C sequestration, and soil resilience against a changing and uncertain climate, and (c) produce more from less land and with less use of water, energy, and agrochemicals by reducing losses and enhancing the use efficiency.

Soil properties and processes are linked to the global issues facing humanity, such as climate change, food insecurity, water scarcity and eutrophication, biodiversity reduction, growing energy demand, and rapid urbanization. Yet, insight from a single disciplinary framework of soil science (pedology, physics, chemistry, biochemistry, or microbiology) and related disciplines (e.g., geology, ecology, plant physiology, or climatology) is not sufficient to resolve these complex issues. Thus, synthesizing and integrating insights from a range of disciplines into an inclusive framework of analysis is critical to creating a viable and a long-lasting solution. The aim is formulating a setting that enables all specialists to devote their best disciplinary efforts toward solving a complex problem, such as soil degradation, soil C and nutrient depletion, elemental and water imbalance, and vulnerability to climate change.

Therefore, the objective of this article is to describe the concept of interconnectivity and the nexus approach to addressing complex issues pertaining to sustainable management of soil for adapting and mitigating climate change through C sequestration and creating climate-resilient agroecosystems, advancing food and nutritional security, improving water quality, and increasing use efficiency of inputs.

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HISTORICAL PERSPECTIVE OF THE NEXUS APPROACH

Ancient civilizations understood the importance of the nexus approach, interconnectivity, the holistic concept, or holism for millennia (Lal 2016). During the Mesopotamian era around 2700 BC, Assyrian King Ashurbanipal promoted "the nature-culture discourse" (Roaf 2004; Pollock 1999). The terra-cotta seals of the Harappan civilization of 3300 to 1300 BC in the Indus Valley (Kenoyer 2003; Conningham and Young 2015) depicted the significance of "the ecological consciousness." The *Rig Veda* (Rajarm and Frawley 2001), authored by the Indo-Aryans circa 1500 to 1000 BC in northwestern India, vividly state the significance of holism: "Everything is a part of the unity, Every part is a constitutive of the whole." In the sixth century BC, Greek philosopher Pherecydes of Syros proclaimed, "Earth as a living organism." Phyerecydes also stated, "Zen is aither, Chthonie is the earth, and Chronsus is time; the aither is that which acts, the earth is that which is acted upon; time is that in which events come to pass" (Schibli 1990). The writings of Plato (248-347 BC) stated, "the Universe as an intelligent living being" (Plato 1952, 2002; Lovelock 1971). Similar views were expressed by Aristotle and are also stated in religious traditions of Hinduism, Buddhism, and others. In the nineteenth century, the German philosopher G.W.F. Hegel put it more succinctly by stating that "the whole is greater than sum of its parts" (Lasson 1921). It was Jan Smuts, a twentieth century South African scientist, who defined holism as "the tendency in nature to form wholes that are greater than the sum of the parts through creative evolution" (Smuts 1926). Interconnectivity of natural processes has also been stressed by John Muir (Fox 1985; Williams 2002) and Barry Commoner (1971).

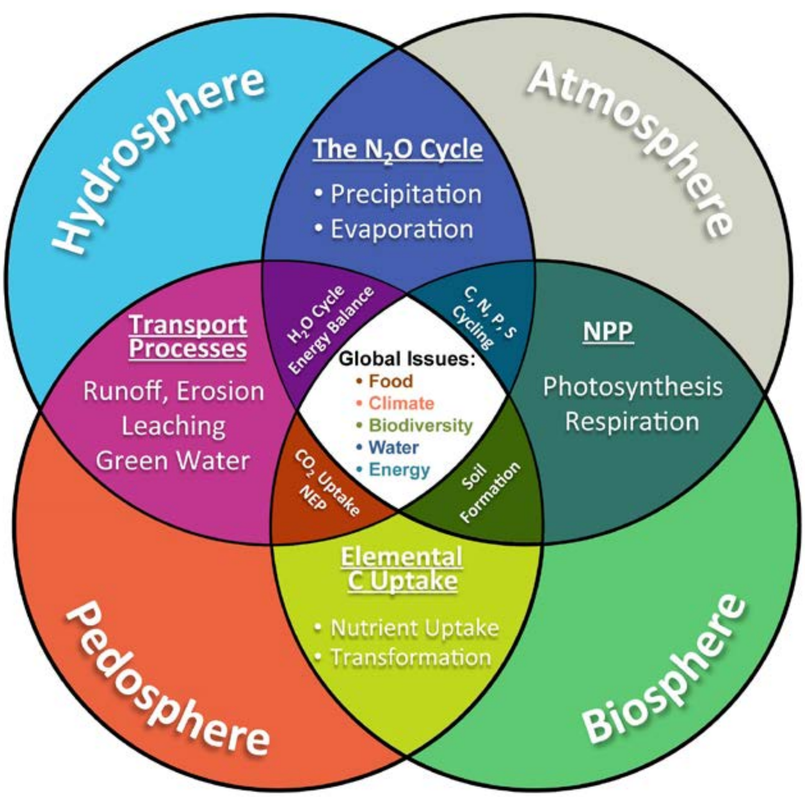
THE NEXUS APPROACH AND GLOBAL ISSUES

Addressing complex global issues necessitates innovative approaches to achieving an environmentally sustainable solution.

Table 1
Ten global issues of the twenty-first century.

Issue	Facts	Reference
Population	7.4 billion in 2015, 9.7 billion in 2050, and 11.2 billion in 2100	UN 2015
Atmospheric chemistry	Carbon dioxide at 400 ppm, methane at 1,833 ppb, and nitrous oxide at 327 ppb	WMO 2015
Anthropogenic emissions	10 Pg carbon from fossil fuel combustion, 0.9 Pg carbon from deforestation	Le Quéré et al. 2015
Land degradation	24% of the world land areas, and affecting 1.5 billion people in 2008	Bai et al. 2008
Algal bloom	Impact water quality in the Great Lakes and Gulf of Mexico in United States, Lake Taihu in China, Baltic Sea in Europe	Lopez et al. 2008; Kudela et al. 2015
Urban encroachment and land sealing	Urban land cover will increase by 1.2 million km^2 by 2030, with loss of 1.38 Pg carbon within the Pan-tropics	Seto et al. 2011, 2012
Biodiversity loss	Rates of extinction of at least several hundred times the rate expected on the basis of the geological records for the past 300 years	Dirzo and Raven 2003; Cardinale et al. 2012
Tropical deforestation in 2010s	7.6 Mha y^{-1}, a region equivalent to the area of Sri Lanka	Achard et al. 2014
Excessive water withdrawal	In Indo-Gangetic Plains, North China Plains, Ogalalla aquifer, etc; water scarcity affecting 2.3 billion in 2000 and 3.5 billion in 2025	Kerr 2009; Bjerga 2005; Li et al. 2014; Liu et al. 2001; IEA 2015
Energy use	550 EJ consumed in 2010 of which 80% is from fossil fuel and 11.3% from wood and other biofuels	Koppelaar 2012; Tverberg 2012

Figure 1
Interactive effects of ecospheres on global issues of twenty-first century. NEP = net ecosystem production. NPP = net primary production. C = carbon. N = nitrogen. P = phosphorus. S = sulfur. N_2O = nitrous oxide. CO_2 = carbon dioxide.



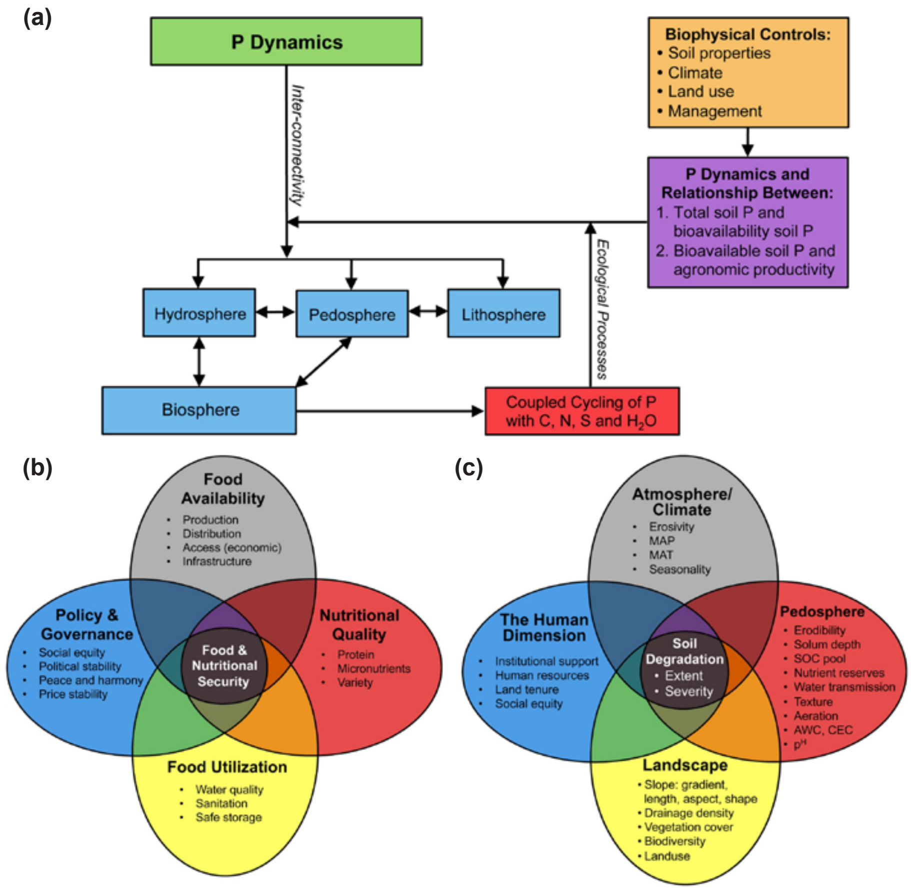
The latter requires a thorough understanding of interactions among the four ecospheres: atmosphere, biosphere, pedosphere, and hydrosphere (figure 1). The net primary production is governed by the interaction between atmosphere × biosphere through nutrient availability from the pedosphere; elemental uptake and nutrient transformations by biosphere × pedosphere; transport processes (e.g., erosion, leaching, and water flow) by pedosphere × hydrosphere; and the hydrological cycle (precipitation, evaporation, and actual evapotranspiration) by hydrosphere × atmosphere. The principal control of secondary interaction involving three ecospheres leading to soil formation and weathering is by atmosphere × biosphere × pedosphere; carbon dioxide (CO_2) uptake and net ecosystem production by biosphere × pedosphere × hydrosphere; and the hydrologic/energy balance by pedosphere × hydrosphere × atmosphere. The tertiary interaction involving all four ecospheres governs the major global issues of the twenty-first century (table 1) including food/nutritional security, climate change, biodiversity, water security, and energy availability. Thus, understanding basic processes and successfully addressing the urgent global issues must also encompass the nexus approach based on synergisms among principal components.

Problems of water pollution, including algal blooms caused by eutrophication of natural waters, are also caused by anthropogenically induced interactions between hydrosphere × biosphere × pedosphere × lithosphere (figure 2a). Similarly, food and nutritional insecurity is governed by the interaction between food availability × nutritional quality × food utilization

× policy and governance (figure 2b). Soil degradation, another global issue of paramount significance, is governed by the interaction between climate/atmosphere × pedosphere × landscape × the human dimension (figure 2c). Social and economic factors are among major drivers of soil degradation.

Figure 2

Interactive effects of ecosphere processes in (a) water quality and algal bloom, (b) food and nutritional security, and (c) soil degradation. P = phosphorus. C = carbon. N = nitrogen. S = sulfur. MAP = mean annual precipitation. MAT= mean annual temperature. SOC= soil organic carbon. AWC = available water capacity. CEC = cation exchange capacity.



SIMPLE SOLUTIONS FOR COMPLEX PROBLEMS

There has been a growing emphasis on the adoption of the nexus approach for addressing complex problems because of the widespread realization that focus thus far has been on only one component of the nexus, which has often aggravated the problems and exacerbated adverse consequences. Thus, understanding the nexus (Hoff 2011; Hanlon et al. 2013) and governing it (Kurian and Ardakanian 2015; Lal 2015) are important to addressing complex global issues of water, food, and energy insecurity (Waughray 2011), especially, and for maximizing synergies and minimizing tradeoffs (McCornick et al. 2008). The enhanced focus on the nexus approach was set-in-motion by the conference in Bonn in 2011, which was organized in preparation for the United Nations "Rio+20 Conference on Sustainable Development." The strategy was to focus on a system approach to address complex global issues. One year after the Bonn conference, the United Nations University Institute for Integrated Management of Material Fluxes and of Resources on Soil-Water-Waste nexus was inaugurated in Dresden, Germany (Lal 2013). The International Institute for Sustainable Development of Canada adopted the Water-Energy-Food Security Nexus to address the complex issue in international development (Bizikova et al. 2013). Similarly, the Austrian Development Corporation (ADC 2015) adopted the nexus approach for its three-year program from 2016 to 2018 with the focus on water sanitation, sustainable energy, and food security. Because of the potential synergies and complementarities among interacting components, the nexus approach to water-energy-food security has also been intensively pursued for adaptation and mitigation of the abrupt climate change (Rasul and Sharma 2015). The water-energy-food nexus has been adopted by the Food and Agriculture Organization of the United Nations (FAO 2014) as a new approach to advancing food security through sustainable agriculture. Indeed the water-energy-food nexus is being used as a conceptual tool for achieving sustainable development (Biggs et al. 2015). The nexus approach has also been used for addressing the poverty-environmental degradation relation (Duraiappah 1998) because of the argument that poverty is a major cause of environmental degradation, and thus also for improving the human livelihood (Biggs et al. 2015). The nexus concept is similar to the focus on the whole-landscape approach for sustainable development (DeFries and Rosenzweig 2010).

GLOBAL FOOD SECURITY AND THE NEXUS APPROACH

World population is projected to grow by 2.3 billion between 2016 and 2050, from 7.4 billion to 9.7 billion (UN 2015), and by then 66% of the world population (6.8 billion) will live in urban centers (UN 2014). With growing income and affluence, the food demand will have to presumably increase by 70% between 2005 and 2050 (FAO 2009). It is estimated that annual cereal production would have to grow by 1 billion t (1.1 billion tn), and meat production by over 200 million t (220 million tn) to 470 million t (518 million tn). In comparison with 2005, the area of arable land will have to be expanded by 70 Mha (173 million ac), or by about 5%, encompassing an increase of 120 Mha (297 million ac) in developing countries and decrease of 50 Mha (124 million ac) in developed countries.

If these assumptions are correct, world cereal production will have to be increased from 2,240 million t (2,469 million tn) in 2008 and 2,470 million t (2,722 million tn) in 2015 to 2,670 million t (2,943 million tn) by 2030 and 3,000 million tn by 2050 (FAO 2009, 2013; Bruinsma 2009). Thus, the cereal demand will have to increase annually by 1%. Further, the projected climate change may reduce food production by 0.5% during the mid-2010s and by 2.3% by the 2050s (Calzadilla et al. 2013). The global land area under cereal production has increased from 697 Mha (1,722 million ac) in 2008 to 705 Mha (1,742 million ac) in 2015.

Yet, the problem is not entirely with the scarcity of grain production but with low access, uneven distribution, and poor utilization. Globally, the food waste is estimated to range from 10% to 50% in both developing and developed economies (Parfitt et al. 2010). As much as 1 billion t (1.1 billion tn) of food never reaches consumers (Gustafson 2016). About one-third of the food overall or one-fourth in kilocalories of the world's crops are lost or wasted (Aschemann-Witzel 2016).

Further, the serious problem is the global scale of malnutrition (table 2). In comparison with 794 million people affected by calorie deficiency, 2 billion are affected by hidden hunger or micronutrient deficiency, 1.9 billion by obesity, and 254 million children (under 5 years) by stunting and low weight (table 2). Therefore, the complex issue of food and nutritional insecurity can only be addressed by a nexus approach of addressing all issues affecting production, storage, processing, distribution, access, and utilization. There is also a need for education of the general public with regards to enhancing the production; small landholders (~500 million worldwide) account for 70% of total food production. The nexus approach must be adopted to enhance agronomic production of about 500 million small landholders around the world.

SOIL RESTORATION AND ENVIRONMENTAL SUSTAINABILITY

Global food and nutritional security is strongly determined by soil and environmental quality. Health of soils, plants, animals, and people are intricately intertwined. Soil degradation is a major cause of malnutrition (Howard 1947; Lal 2009), especially in developing countries. Thus, food and nutritional security can only be addressed by restoring soil health and environmental quality. The extent and severity of soil degradation are affected by interaction between climate, soil type, landscape, and the human dimensions (figure 2c). Therefore, strategies for restoration of soil and environmental quality must also consider interacting effects of biophysical and socioeconomic factors. Restoration of soil quality, through C sequestration, is an important strategy. Thus, implementation of the "4 per Thousand" (4PT) program (Chambers et al. 2016), is a high priority and also needs nexus thinking.

To be effective in advancing food/nutritional security while adapting to and mitigating the climate change, implementation of 4PT must be objectively planned. It must also achieve the Sustainable Development Goals of the United Nations (UNDP 2015): eliminating hunger, alleviating poverty, improving livelihood, empowering women and minorities, and developing climate-resilient soils and agroecosystems. Therefore, a system approach based on nexus thinking is also pertinent. While assessing the biophysical impacts of implementing 4PT (on regional, national, or global scale), it is also essential to consider the socioeconomic and governance issues related to the management of natural resources. Important among biophysical processes are impacts of soil C sequestration on soil quality and functionality, agronomic/biomass productivity, use efficiency of inputs, changes in water quality, rate and type of gaseous emissions, above- and belowground biodiversity and soil microbial processes, and the C footprint of production systems. Similarly, the human dimensions (e.g., nutritional quality of food and water and their impacts on human wellbeing, social and gender equity, and household income) must be considered.

In addition to the impact, the adoption of recommended management practices for C sequestration by farmers and land managers may necessitate payments for provisioning of ecosystem services (e.g., sequestration of C for adaptation and mitigation of climate change, improvement of water quality and renewability, and enhancement of biodiversity).

Any payment for provisioning of ecosystem services must be made on the basis of the societal rather than the economic value. For example, the societal value of soil organic C is estimated at \$120 t^{-1}(\$108.9 tn^{-1}) (Lal 2014). Payments must also be based on credible rates of soil organic C sequestration measured at landscape or the farm scale. Thus, C farming is a boon for the soil and the environment.

CONCLUSIONS

Effective solutions to global issues require a system approach based on nexus thinking to enhance synergisms, minimize tradeoffs, and reduce environmental footprint. The concept has been considered throughout the human history by ancient civilizations. Indeed, environmental problems of the Green Revolution could have been reduced through a farming system approach to agricultural intensification.

Table 2

Global scale of malnutrition.

Type	Population affected (10^9)	Reference
Micronutrient deficiency	2.0	WHO 2015a
Obesity	1.9	WHO 2015b
Children under 5		UNICEF, WHO, and World Bank 2013
• Stunting	0.161	
• Low weight	0.051	
• Obese	0.042	
Calorie deficient	0.794	FAO 2015a, 2015b
Type 2 diabetes	0.091	WHO 2015b
Total	5.039	IFPRI 2015

Simplified systems of growing improved varieties with high inputs of chemical fertilizers and supplemental irrigation have exacerbated the depletion of ground water, eutrophication of surface waters, and pollution of the environment. Thus, adopting the conceptual tool of the nexus or system approach based on new thinking is critical to meeting the ever-growing demands of the increasing and affluent world population. Indeed, understanding and implementing the water-food-energy nexus is also essential to advancing the Sustainable Development Goals of the United Nations.

While the challenges of sustainable management of soil and water resources to meet the demands of humanity have existed ever since the dawn of agriculture, the solutions to these problems have changed over the history of human civilizations depending upon available knowledge and technological development. While the nexus approach will not solve the problems of humanity forever, it is a starting place as we develop more innovative concepts through advances in science and evolution of philosophical thinking.

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