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REPORT

Reconciling food security and bioenergy: priorities for action

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Abstract

Understanding the complex interactions among food security, bioenergy sustainability, and resource management requires a focus on specific contextual problems and opportunities. The United Nations' 2030 Sustainable Development Goals place a high priority on food and energy security; bioenergy plays an important role in achieving both goals. Effective food security programs begin by clearly defining the problem and asking, 'What can be done to assist people at high risk?' Simplistic global analyses, headlines, and cartoons that blame biofuels for food insecurity may reflect good intentions but mislead the public and policymakers because they obscure the main drivers of local food insecurity and ignore opportunities for bioenergy to contribute to solutions. Applying sustainability guidelines to bioenergy will help achieve near- and long-term goals to eradicate hunger. Priorities for achieving successful synergies between bioenergy and food security include the following: (1) clarifying communications with clear and consistent terms, (2) recognizing that food and bioenergy need not compete for land and, instead, should be integrated to improve resource management, (3) investing in technology, rural extension, and innovations to build capacity and infrastructure, (4) promoting stable prices that incentivize local production, (5) adopting flex crops that can provide food along with other products and services to society, and (6) engaging stakeholders to identify and assess specific opportunities for biofuels to improve food security. Systematic monitoring and analysis to support adaptive management and continual improvement are essential elements to build synergies and help society equitably meet growing demands for both food and energy.

Keywords: bioenergy, biofuels, energy, flex crops, food insecurity, food security and nutrition, natural resource management, poverty reduction, sustainable development goals

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> The most serious mistakes are not being made as a result of wrong answers. The truly dangerous thing is asking the wrong questions. —Peter Drucker (1971)

Introduction

Understanding the nexus of food security, bioenergy sustainability, and resource management facilitates achievement of the 2030 Sustainable Development Goals (SDGs) to end hunger and ensure access to modern energy for all (United Nations (UN) 2015), as well as the Paris Agreement under the UN Convention on

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Climate Change. Contextual conditions determine costs, benefits, and strategic opportunities that foster food and energy security for all (DeRose *et al.*, 1998; FAO, 2015b; FAO, IFAD and WFP 2014). However, it is important to acknowledge that public perception about the interaction of bioenergy, in particular biofuels, and food security is mostly negative. Popular media reinforce beliefs reflected in the assumption used in economic models that biofuels produced from crops or on cropland compete with food production and increase food prices. Cartoons of hungry children juxtaposed to corn being ‘fed’ to cars have generated an emotional response to biofuel policies that is difficult to overcome (Osseweijer *et al.*, 2015; The Economist, 2015). Sensational news garners attention while subsequent corrections are overlooked (Flipse & Osseweijer, 2013). In this report, we review the underlying evidential and theoretical basis concerning the impacts of bioenergy, in general, and biofuels, in particular, on food security and offer steps that can help society achieve SDGs for food and energy security.

A science-based examination of evidence linking food security and bioenergy illuminates practical solutions when problems are well defined. Good science is essential to inform decisions in a world of strong beliefs (Hecht *et al.*, 2009). An initial step must be to understand relationships between biomass production, food production, and hunger. Food security is recognized as a fundamental human right (UN General Assembly, 2015) with modern energy services being an essential component of food production, supply, and preparation (Woods *et al.*, 2010).

This study describes the complexities in assessing sustainability as related to energy and food security in four parts: (1) food security, (2) interactions among food security, biofuels, and resource management, (3) priorities and conditions for achieving positive synergies, and (4) conclusions and recommendations. We begin by recognizing that food insecurity is typically the indicator, so linkages among resource management, biofuels, and strategies to reduce food insecurity are relevant. We highlight where conventional wisdom could be misleading and identify areas where further research should be a priority. The paper concludes with recommendations for enhancing food and energy security as complementary goals for sustainable development.

An international workshop (IFPRI, 2015) helped frame the key issues evaluated here and underscored the importance of clear definitions and consistent use of terminology. The workshop focused on liquid biofuels, but the discussion and conclusions in this paper aim to be broadly applicable to food security interactions with an expanding bio-based economy. Polarization in the food-vs.-fuel debate begins with differing definitions and assumptions about relationships among biofuels, prices, food, and land security. It is important to analyze the reasons for divergence and to find common ground (Rosillo-Calle & Johnson, 2010).

Food security

Definitions and measures of food security

The definitions used for food and food security are important determinants of the scope and outcomes of analyses. The oft-cited definition from the Food and Agriculture Organization of the United Nations (FAO) reflects broad aspirational goals (FAO 1996, Table 1). Four dimensions of food security emerge from this definition, namely, availability, accessibility, stability, and utilization (Table 2). Thus, one approach to assessing impacts of biofuels on food security examines interactions across these four dimensions. However, many other factors including distributional and contextual issues affect vulnerability and hunger (von Grebmer *et al.*, 2014).

Measuring food insecurity. While the concept of food security is intuitive, underlying data are fraught with uncertainties due to large variations in diets and biophysical conditions, making food security difficult to measure and monitor. Therefore, *manifestations of food insecurity that can be observed and verified* are often used as proxy indicators of hunger and are monitored, rather than monitoring food security itself. For example, three international organizations collaborate to produce annual reports on the ‘State of Food Insecurity in the World’ (SOFI) (e.g., FAO, IFAD and WFP 2015a, 2014, 2013, FAO, WFP, IFAD, 2012, and previous years).

The terms food security and food insecurity are often used loosely or interchangeably; however, the definitions and approaches for their measurement vary considerably (DeRose *et al.*, 1998). Anthropometric measures of food insecurity are complemented by qualitative surveys of behavior from census data on household income and expenditures. Undernourishment, a common measure of food insecurity, is the probability that an *individual* in the population is undernourished (FAO, 2015a), while other measures focus on household food purchases (USDA, 2015; Coleman-Jensen *et al.*, 2015). A global hunger index combines three equally weighted indicators: (1) undernourishment, defined as people with insufficient caloric intake (percentage of population); (2) children under the age of five with low weight for their age; and (3) mortality rate for children under age five (von Grebmer *et al.*, 2014, Gautam, 2014). The effects of biofuels or a given policy on ‘food insecurity’ thus depend on the measures used to define who is ‘food insecure.’

Table 1 Definitions relating to food security (based on IPC Global Partners 2012 and other sources as noted)

Term	Definition/Examples
Anthropometry	Study of the measurements and proportions of the human body; used as an indicator of malnutrition. Examples include child underweight (weight for age), stunting (height for age), and wasting (weight for height), compared with reference standards (United Nations World Food Program (WFP) Hunger Glossary, 2015)
Commodity	Traded item, especially unprocessed materials. Relevant examples include crude palm oil, raw sugar, #2 yellow corn, wheat, soybeans
Commodity price index	Mathematical value used to measure commodity price movements over a defined time period; typically based on prices registered between suppliers or nations
Consumer food price index	Mathematical measure of price movements over a defined time period for a fixed basket of food items in a given nation, state, region, or group
Famine	Food insecurity causing or potentially causing death in the near term
Food	Source of nutrients required for energy and growth
FAO food price index	Monthly change in international prices of a basket of five food commodity groups (cereals, oils, dairy, meats, sugar), weighted per average export share values of each group for a given period, for example, 2002–2004 (FAO, 2013a)
Flex crop	Cultivated plant grown for both food and nonfood markets.
Food security	Condition that exists when all people, at all times, have physical and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life (FAO, 1996)
Food insecurity (chronic or transitory)	Absence of food security; condition exists when people suffer or are at risk of suffering from inadequate consumption to meet nutritional requirements; may be classified as chronic (long term), acute (transitory), cyclical, or critical (see famine); typically measured via multiple indicators of malnutrition
Hunger (or 'food deprivation')	Degree of discomfort or unpleasant physical sensation associated with insufficient food consumption. World Food Program defines hunger as 'Not having enough to eat to meet energy requirements.' The World Hunger Education Service (2015) refers to hunger as 'aggregated food scarcity exemplified by malnutrition.'
Malnutrition	Condition arising from deficiencies, excesses, or imbalances in the consumption of important macro- and micronutrients. Malnutrition can arise directly from food insecurity or be a result of (1) inadequate childcare practices, (2) inadequate health services, (3) a harmful environment, or (4) excessive intake of unhealthy food
Poverty	State of being that encompasses multiple dimensions of deprivation relating to human capacity and capability, including consumption and food security, health, education, rights, security, dignity, and decent work
Social safety nets	Public programs that provide assistance, often as income transfers, to families or individuals who are unable to work or are temporarily affected by natural disasters, political crises, or other adverse conditions. Programs may involve (1) direct and targeted feeding (school meals, soup kitchens, or food distribution centers), (2) food-for-work programs, (3) cash or in-kind transfers (e.g., food vouchers), (4) subsidized rations, or (5) other support to targeted households
Staple food	Principal or recurring food ingredient in a regional diet

Price indices alone are not indicators of food security. Given the high cost and complexity of field measurements, broad indicators related to prices and regional balances of commodity supplies and utilization are often used for food market assessments. Price, supply, and trade data are readily available from existing sources and do not require primary fieldwork to gather. Further, because these data can be easily plugged into existing market equilibrium models, they have been widely used to estimate the effects of biofuels on food security. Yet, as discussed below, there is little evidence that price indices can tell us much about who actually suffers from malnutrition due to food insecurity or its primary causes. Despite correlations, changes in global commodity prices are distinct from changes in consumer food price indices (Fig. 1).

Table 2 Questions and trade-offs to consider when assessing effects of bioenergy across four dimensions of food security (food security dimensions based on FAO, 1996, 2008)

Dimensions of food security	Key questions: Does the proposed project increase or decrease…	Assessment considerations	Trade-offs
Availability: quantity available for consumption in markets or within households	The quantity of food, especially staples, available for household consumption? coping mechanisms and institutional capacity to respond in times of crisis? quantity of food required for traditional cultural practices and identity?	Which dimensions of food security are the primary causes for food insecurity or risk of insecurity in this area? Which households/subgroups of the local population are most food insecure at present and why? Which households and subgroups are at highest risk of becoming food insecure, given current local trends and the context of the proposed project? How does local energy use interact with food production, transport, preparation, and processing?	Can improvement in one dimension offset reductions in another? Will critical aspects for local food security or insecurity be affected? Will the project make clean energy services more affordable or widely available? Who gains and who loses in each dimension? How are project impacts distributed among groups, particularly food-insecure and at-risk groups?
Accessibility: affordability or other aspects of securing available food	Affordability of food, particularly for low-income households or other at-risk groups? investment in roads, bridges, public transport, or other features that facilitate access to markets and services (particularly in times of crisis)? factors that have caused disruptions in access to food in the past for this area?		
Stability: volatility in prices, availability, or affordability	Market 'floors' or 'ceilings' that reduce price fluctuation in staple foods? diversity of markets for producers (e.g., higher or lower dependence on single buyer or use)? diversity of food sources? diversity of sources of income? the base area of production of staple foods (e.g., changing susceptibility to localized extreme weather events)? other price and supply volatility impacts?		
Utilization: retention and use of the nutrients in consumed food to sustain health and well-being	Nutritional value of diet for at-risk population? health and sanitation services? education for at-risk populations? micronutrient deficiencies? food safety, general health, and other factors influential in utilization?		

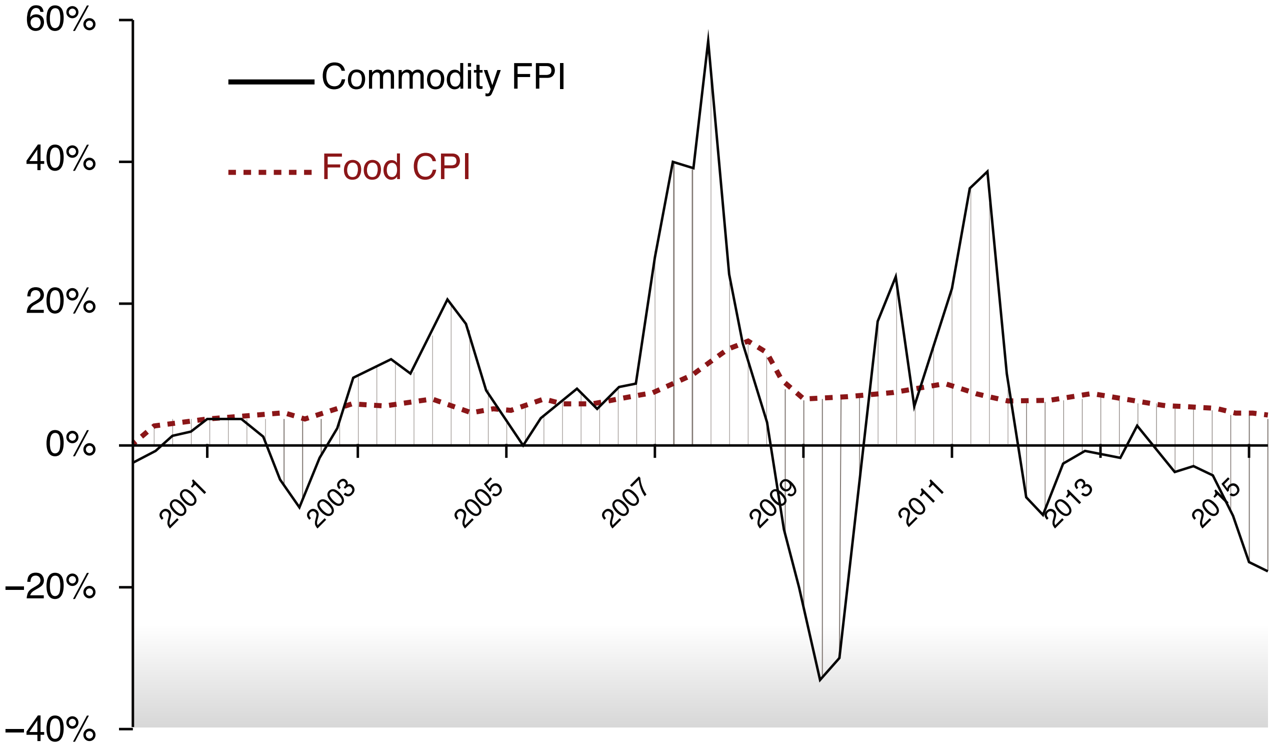

Fig. 1 The FAO global Food Price Index (FPI) based on commodities vs. the FAO global food Consumer Price Index (CPI), 2000–2015 (FAOStat, 2015). See Table 1 for definitions. Percentage change is relative to the 2002–2004 average for FPI and year 2000 for CPI (FAO, 2015c). The food CPI increased each year at an average annual rate of 6% (2000–2015), while the annual average global FPI varied sharply and was negative in 7 of the 15 years.

FAO notes that its food price index (FPI) is not an indicator of food insecurity. Rather, the FPI is based on weighted indices of trade data (Table 1) which may not reflect: (1) foods needed by food-insecure countries; (2) price changes relevant to food security; and (3) the actual prices for households which ‘may be quite different from the border prices’ (FAO, 2013a). Furthermore, in nations where high numbers of people are food insecure, staples such as rice are managed or regulated explicitly to protect local consumers from external price fluctuations (FAO, 2014, 2015c). Finally, FPI weighting creates bias favoring expensive commodities that are less important for populations at risk; for example, meat has the highest weight, 0.35, while sugar has a weight of 0.07.

National and regional ‘consumer food price indices’ (CFPIs) provide a higher resolution than the FPI but are still insufficient indicators of food insecurity due to similar dollar-value weighting bias and reliance on formal market prices. The people most susceptible to severe food insecurity typically live in isolated areas and rely on informal markets or subsistence production (Rose, 1999; FAO, 2015a; FAO, IFAD and WFP, 2015b). Rice, wheat, millet, white maize, and yams are staples in Asia and Africa, where 94% of the world’s hungry reside (FAO, 2015a), but their local prices have minimal influence on CFPI values. When these staples are grown and consumed locally, they are omitted by both the aggregate trade models and CFPIs, despite being crucial sources of nutrition for vulnerable households.

The annual SOFI reports highlight dozens of context-specific factors, other than CFPI changes, that determine who goes hungry in times of crisis (e.g., FAO, WFP, 2010). Malnutrition is associated with many factors other than food intake (e.g., Smith & Haddad, 2000; Gautam, 2014; Lombard, 2014). Thus, biofuel effects on food security could be determined by a project’s influence on physical infrastructure, asset accrual, institutional capacity, training, technologies that enhance food safety or resilience, ecosystem stability, cultural well-being, or other drivers and coping mechanisms omitted from food price indices (Rose, 1999; RTI, 2014; Coleman-Jensen *et al.*, 2015; Gustafson *et al.*, 2016).

Finally, analyses that rely on FPIs tend to focus on price spikes while ignoring long periods of depressed prices. This can mislead policymakers and the public because depressed prices discourage agricultural investment and can be more detrimental to long-term food

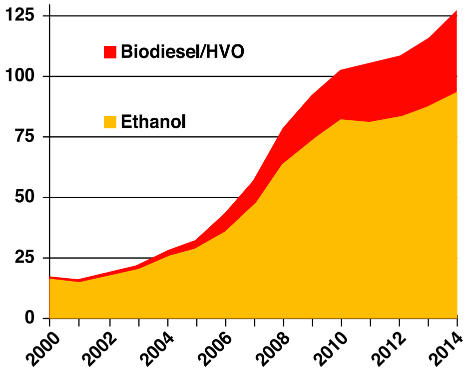

Fig. 2 Global biofuel consumption (billion liters) 2000–2014 grew steadily, although fuel ethanol production dipped slightly in 2010–2012 due to global recession and poor weather in Brazil (in 2011) and the USA (in 2012). Still, average annual growth in global production over 2009–2014 remained robust, at 5.2% and 11% for fuel ethanol and biodiesel, respectively (REN21, 2015). Chart based on U.S. Energy Information Administration (2015) and REN21, 2015.

security than price spikes (see, e.g., the SOFI reports and Roser, 2015). Projects that contribute to price stability at a level high enough to motivate local investment in food production and its associated infrastructure will improve resilience and food security over the long term (FAO, IFAD, WFP, 2002).

Effective food security strategies address relevant risk factors

To assess how a policy or project affects food security, an understanding of risk factors that lead to food insecurity is needed. As described above, analysis of aggregate commodity data may generate conflicting conclusions, because correlations with biofuels are often extraneous to the causes of local food insecurity. Understanding why and how people become food insecure is prerequisite to developing effective responses. Food insecurity may involve distinct risk factors depending on whether effects are long term (chronic) or short term (acute or transitory).

The type and cause of food insecurity in a particular context determine appropriate responses (IPC Global Partners, 2012) and how the effects of a bioenergy project on food security should be assessed (Table 2). Addressing chronic food insecurity requires coordinated commitments to long-term strategies that reduce household vulnerabilities. Transitory food insecurity requires investments that mitigate or prevent sudden events that can limit access to adequate food for short periods. Transitory food insecurity may be caused by events that impede distribution from areas of food surplus to areas of need (e.g., loss of critical bridge or road). Thus, the degree to which biofuel production and processing may influence food security depends on the interaction of many variables within a local context including, among others: what feedstocks are grown and where and how feedstocks are distributed, what investments are made, management practices, who benefits, and who loses (Table 2).

Biofuels and food security: short-term correlations vs. long-term trends. The high-profile expansion of ethanol production in the United States and Brazil, in tandem with a global price spike in food and commodities in 2007–2008, led many to contend that a causal relationship exists between biofuels expansion and food insecurity (e.g., Mitchell, 2008; Tenenbaum, 2008; Wenzlau, 2013). The apparent short-term correlations are often cited as evidence of negative impacts of biofuels on food security (e.g., EPI, 2014; Searchinger & Heimlich, 2015). There are several problems with such assertions (Zilberman *et al.*, 2013). First, many studies attribute the food price spikes in 2008 primarily to other factors such as oil prices, economic growth, currency exchange rates, and trade policies (e.g., Baffes & Dennis, 2013; Konandreas, 2012; HLPE, 2011; Foresight, 2011; Trostle *et al.*, 2011; DEFRA, 2010). Speculation in food commodities also contributed to price spikes in 2008 and 2011 (Lagi *et al.*, 2011; Hajkowicz *et al.*, 2012). Second, the correlations did not persist as global biofuel consumption continued to grow (Fig. 2) and cereal prices fell or showed distinct patterns over the last 6 years driven by oil price, national agricultural policies, and exchange rates (FAO, 2015a,c, The Economist Intelligence Unit, 2015). Causation cannot be assumed based on correlation, but the divergence in recent trends is notable, and models using the same data can reach opposing conclusions (Table 3).

A majority of papers and reports that assert that biofuels harm food security rely on assumed relationships between biofuels, rising global ‘food’ commodity prices, and food insecurity over relatively short time spans (e.g., on the order of months) (Boddiger, 2007; Rajagopal *et al.*, 2007; Tenenbaum, 2008; Wenzlau, 2013). Interestingly, organizations wishing to show that biofuels do not raise food prices often cite the same FAO ‘food commodity’ data over similar time spans (e.g., see Zhang *et al.*, 2010; Mueller *et al.*, 2011; and GRFA, 2015). The assumptions underlying both sides of this food-vs.-fuel debate are questionable and subjective (Table 3). Long-term trends (over years and decades) for food insecurity and food commodity prices illustrate that the world’s most severe famines (Roser, 2015) occur during extended periods of depressed global food prices (Sumner, 2009). The emphasis on biofuels and food commodity price spikes has diverted attention from more

Table 3 Identical data can support contradicting hypotheses about nutritional effects of biofuel-food interactions

Observations: Despite population growth, 167 million fewer people suffered from hunger and undernourishment in 2015 than a decade earlier (FAO, 2015a). Over the same decade, biofuel production expanded rapidly along with the number of people suffering early mortality and disease from consuming too much of the wrong foods. Today, more people are malnourished from overconsumption than are undernourished due to insufficient food. Over the coming decade, the global population suffering from hunger is projected to decline, while the number suffering from diseases caused by overconsumption is projected to steadily rise (WHO, 2015)

Hypothesis 1	Hypothesis 2	Hypothesis 3 (conventional wisdom)
Hypothesis 1: The effect of biofuel production on the price of food is most pronounced for commodities that compete directly with bioenergy feedstock. Sugarcane and yellow maize are the two most important biofuel feedstocks. The primary foods derived from sugarcane and yellow maize are sugar and other sweeteners (such as high-fructose corn syrup used globally), and red meat (most yellow maize is fed to cattle). These foods are among the primary sources of malnutrition from overeating (WHO, 2015). If biofuels cause higher prices and higher prices marginally reduce overconsumption, then the expected impacts on health would be beneficial	Hypothesis 2: The effect of biofuel production on the price of food is most pronounced for commodities that compete directly with bioenergy feedstock. Sugarcane and yellow maize are the two most important biofuel feedstocks. Bioenergy markets bolster investment and innovation, reducing long-term costs and increasing global supplies of said commodities. The primary foods derived from sugarcane and yellow maize (sugar, sweeteners, red meat) are more widely available at lower prices than would occur without biofuels. Thus, the impacts would be detrimental to health if biofuels drove sugar and yellow maize prices down so as to marginally increase overconsumption of red meat and sweeteners	Hypothesis 3 (conventional wisdom): The effect of biofuel production on the price of food is most pronounced for commodities such as maize that compete directly with bioenergy feedstock. Biofuels also compete for land, reducing production of other crops. This reduces food supply or increases food prices, thereby contributing to increased hunger. Evidence cited in this paper refutes most assumptions underlying this hypothesis. Whether the issue is hunger or overconsumption, who is impacted depends on who is at risk of malnutrition and other contextual conditions that determine causal relationships. Specific nutrition problems must be clearly defined to identify effective solutions

Conclusion: None of the hypotheses above can be endorsed because they are not supported by evidence of price transmissions to the specific populations at risk. Despite a rapid increase in biofuel production, there is no evidence of biofuel impacts on food-related health, either beneficial or detrimental. Models that simulate demand shocks from biofuels necessarily show price transmission and reduced consumption, but evidence is lacking to support either the assumed ‘shock’ or the assumed impacts on people at risk. To test a hypothesis, the problem must be clearly defined and the linkages between biofuels and impacts on behavior verified

constructive efforts to improve data (Gibson, 2013) and to identify effective mechanisms to address the food security issues that matter most, namely those having an impact on human health and morbidity.

Priority actions to reduce risks of food insecurity. Biofuel projects can address food security concerns by applying best practices that reduce exposure to risks of food insecurity (Table 4). Many recommendations for investments in biofuels tailored for developing nations have been published (UNCTAD, 2014; FAO 2010, 2011a, 2015b; FAO, IFAD, WFP, 2002, FAO, IFAD, WFP 2013).

Lifting people out of poverty is essential to reduce hunger (von Braun *et al.*, 2009, FAO, IFAD, WFP, 2014, 2015b; Coleman-Jensen *et al.*, 2015). The creation of stable, gainful, rural employment is a high-priority, poverty-reduction strategy (Conway and Wilson, 2012; FAO, IFAD, WFP, 2015b). Improvement in rural household incomes is proposed as a proxy indicator for improvement in food security when assessing the sustainability of biofuels projects (Dale *et al.*, 2013).

Bioenergy projects that improve resilience can reduce vulnerabilities that lead to food insecurity (Gustafson *et al.*, 2016). Resilience refers to the ability of the system to recover following disturbance, and vulnerability refers to inability to withstand a hostile situation. Reducing risk exposure might take the form of facilitating the transition of households from livelihoods that are subject to high levels of variability – such as low-level subsistence farming dependent on a single crop – toward more stable sources of revenue and income.

Exposure to risk can also be reduced by programs that help build rural assets and diversify income sources. If the exposure of households to environmental or socioeconomic shocks cannot be reduced, then a bioenergy project might aim to increase the capacity of vulnerable households to cope with shocks when they arise. Resilience is achieved by ‘strengthening sustainable local food systems, and fostering access to

Table 4 Examples of convergence among recommended practices to enhance food security and to produce sustainable biomass for bioenergy (based on FAO, IFAD, WFP 2002; FAO, 2010, 2011a, 2013b, 2014b, 2015b, 2015e; FAO, IFAD, WFP 2013, 2015b; IMF, 2013; UNCTAD, 2013, 2014; World Bank, 2015)

Dimension	Recommended practices
Access to land, water, and markets	Consultation with stakeholders including smallholders Mapping of customary rights and communal environmental services Fair compensation to owners and traditional users Rule of law and fair mechanisms for conflict resolution Infrastructure to access inputs and markets
Employment	Adherence to international conventions (e.g., International Labour Organization guidelines) Reliable local jobs and healthy working conditions Access to education, vocational skills, and safety Incentives to expand local production Removal of barriers to trade and market information
Income generation	Contracts with local goods and service providers (e.g., profit-sharing options) Freedom of association and collective bargaining Access to credit and business management training Fair and transparent pricing Stable regulatory environment
Local food security	Integrated food and energy systems Improved output and nutritional value from urban gardens and small farms Provision of agricultural inputs, technologies, and equipment Training that is relevant for developing coping strategies (asset building, etc.) Distribution and storage systems
Community development	Improved local infrastructure (transportation, water, schools, etc.) Women in leadership positions Health and safety services and emergency assistance Microlending and financial support mechanisms Social welfare organizations
Energy security	Improved energy infrastructure and maintenance Energy for agricultural technology: cultivation, marketing, irrigation, etc. Bio-based fuels and improved stoves for healthy food preparation Clean, affordable, and reliable energy for value-added processing Equitable and open energy markets
Cross-cutting aspects	Recognition that problems and solutions are context specific Focus on women, the poor, and small producers Transparency Access to financial, technical, 'safety nets' and other social services Environmental sustainability

productive resources and to markets that are remunerative and beneficial to smallholders' (FAO, 2015d).

Interactions among bioenergy, food security, and resource management, focusing on more sustainable systems

Making progress toward sustainable development goals requires attention to provision of social and ecosystem services as well as economics across integrated production systems. Sustainability involves assessing trade-offs among multiple dynamic goals and striving for continual improvement, rather than achieving a specific state. Assessments should compare the relative merits of alternative trajectories in meeting goals. The trade-offs depend on historical developments and prevailing local economic, social, environmental, political, and cultural conditions (Efroymson *et al*., 2013). Because sustainability is context specific, local stakeholders should help set priorities, define the purposes of the assessment, and establish the temporal and spatial boundaries for consideration (Tarka-Sanchez *et al*., 2012; Dale *et al*., 2015). For example, dimensions of sustainability for bioenergy include soil quality, water quality and quantity, greenhouse gases, biodiversity, air quality, productivity, social well-being, energy security, trade, profitability, resource conservation, and social acceptability (McBride *et al*., 2011; Dale *et al*., 2013).

Choices inevitably involve trade-offs. Improving one aspect of sustainability may compromise another, and benefits for one group may involve costs for another (Table 2). Complete transformation chains rather than single bioenergy products should be analyzed to understand the interactions across sectors and industries that may influence system efficiencies for bioenergy and food security (Hilbert, 2014). A key goal is to identify opportunities where collective progress can be achieved – sometimes referred to as the triple bottom line of social, economic, and environmental benefits.

Resource management practices are more important in determining many environmental impacts than crop type (Davis *et al*., 2013). Wise management of available resources supports both bioenergy sustainability and food security (Manning *et al*., 2014). Hence, interactions among resource management, bioenergy sustainability, and food security are discussed with paired interactions considered first, followed by the three-way nexus (Fig. 3).

Two-way linkages

Bioenergy effects on food security. Bioenergy can foster social development, which is a precondition for food security and sustainability. Bioenergy provides energy security not only for transport (and hence broader access to food, selling markets, employment, and services) but also for food processing, business development, and drying and storage of surplus production (Durham *et al*., 2012; Lynd *et al*., 2015). The latter, providing an outlet for surplus, diversifies sources of income and improves supply resilience in the event of market shocks or shortages. Innovation is stimulated as new institutions and actors are empowered to engage in expanding biomass production. The early investments made by developed, developing, and emerging economies alike in biofuels illustrate the universal nature of the linkages between energy security and development (Johnson & Silveira, 2014).

The capacity for biofuels to help balance another commodity market has been demonstrated by the Brazilian sugar–ethanol industries. Similarly, U.S. ethanol

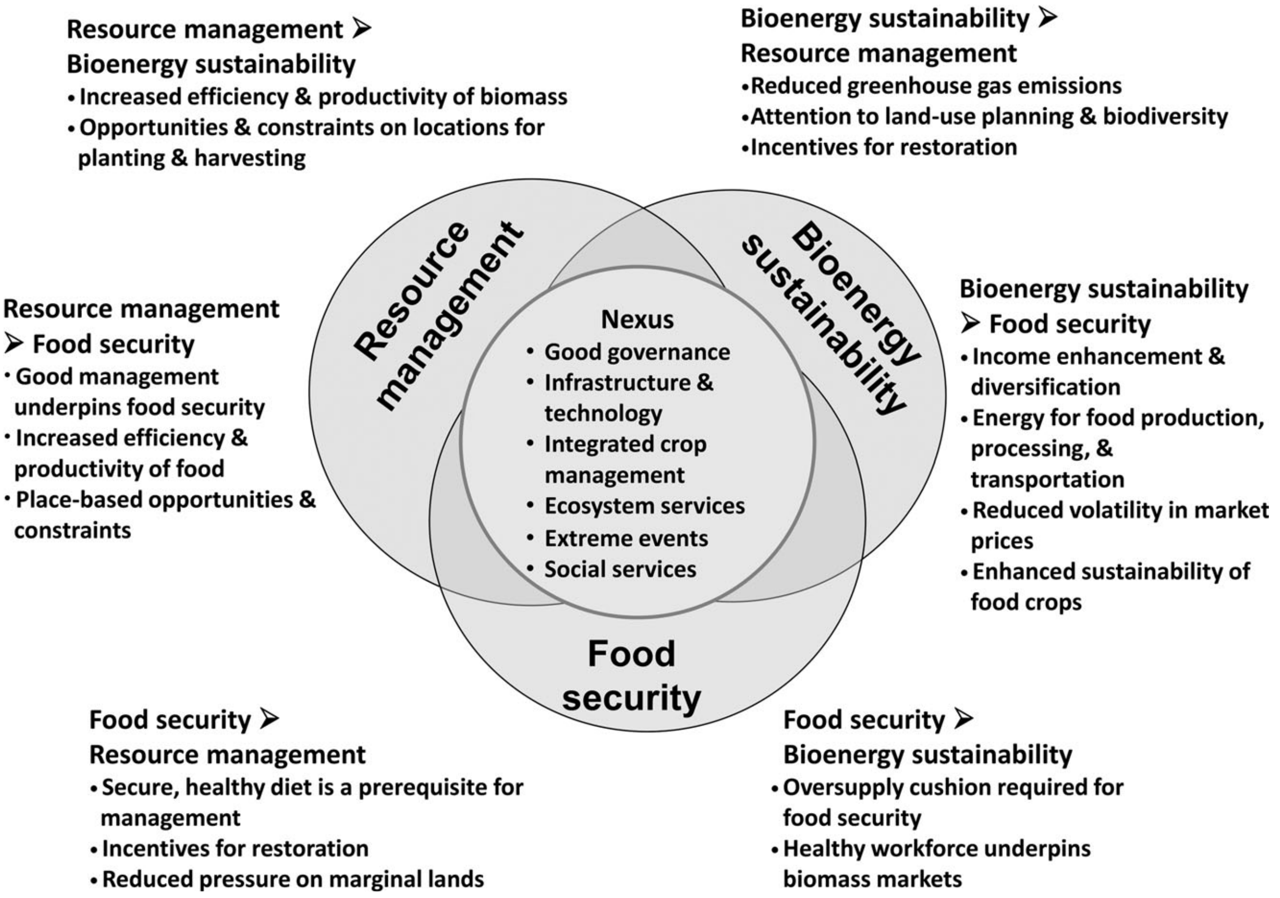

Fig. 3 The nexus of resource management, bioenergy sustainability, and food security. Key aspects of the six two-way interactions frame the nexus at the center.

legislation passed in part due to recognition of latent productive capacity for maize. In the decade leading up to 2012, U.S. maize production increased steadily and exceeded targets for fuel blending under national legislation. In 2012, the U.S. experienced the most extensive drought recorded since the 1950s (IMF, 2012; USDA, 2013). As impacts of the drought became evident, markets responded; some ethanol plants reduced output; others shut down temporarily. Thanks, in part, to the ethanol 'supply cushion' and market flexibility, there was not a notable jump in commodity prices as the 2012–2013 crop was harvested, despite a drought affecting 80% of U.S. agricultural land.

While several studies discuss potential negative effects of biofuels, few examine the ways that biofuels can positively influence food security. First, adequately planned biofuel production can add value, stabilize, and diversify rural production systems (Kline *et al.*, 2009). Additionally, energy is required throughout the food supply chain; therefore, to the degree that biofuels enhance sustainability and accessibility of energy supplies, particularly energy for households most at risk from poverty, they enhance food security. Furthermore, as long as farmers and agro-industry are free to respond, diversified markets for products can spread risk and reduce price volatility compared with more narrow markets. Adding bioenergy markets to existing uses of local produce can thereby increase price stability. Finally, efforts to enhance sustainability of biofuels have generated spin-off effects in other sectors and placed greater scrutiny on resource management associated with conventional production (Woods & Kalas, 2014). The result is improved sustainability for many nonbiofuel products that constitute the majority of final uses for palm oil, sugar cane, soybean, and maize.

Bioenergy effects on resource management. Bioenergy has spurred well-known efforts to develop best practices that reduce greenhouse gas emissions and negative impacts on soil and water. However, bioenergy sustainability has also called attention to land-use planning and biodiversity protection and provided increased incentives for land restoration (Souza *et al.*, 2015). Specifically, bioenergy sustainability calls for consideration of a diverse set of potential effects on water, soils, air, and biodiversity, with emphasis on understanding baseline conditions and setting targets for continual improvement. These are key steps toward implementation of resource management systems that are resilient and adaptable to climate change.

Resource management effects on bioenergy. In turn, improving resource management influences bioenergy sustainability by increasing the efficiency and productivity of supply chains. Improved management of soils and water permits higher output of bioenergy, food, and other products coupled to enhanced nutrient and water use efficiencies (FAO-UNEP, 2011). Past and future resource management goals help define both opportunities and constraints for cultivating more sustainable feedstock crops.

Resource management effects on food security. Good resource management underpins food security. Increased efficiency and productivity of crops enhance resilience and are essential for secure food availability. Similar to biofuel sustainability, good resource management allows identification of place-based opportunities and constraints and enhances the efficiency of resource use.

Food security effects on bioenergy. Food security can affect biomass resource management in many ways. A secure, healthy diet provides the biophysical and socioeconomic basis for managing soil, water, nutrients, and related resources. Excess production, desirable to enhance food security as a precautionary measure, can be absorbed by bioenergy markets and expand income opportunities for farmers when that supply cushion is not needed for sustenance.

Food security effects on resource management. Improving food security can reduce pressures on forests and marginal lands, thereby avoiding erosion and other negative consequences for soils, water, and ecosystem functions. Food-secure families are less inclined to risk health and livelihood to set off to distant frontiers and clear new land, whereas migration is often a last resort for food-insecure families. Food-secure families are also less likely to feel a need to cultivate on steep slopes and other fragile areas that involve physical and legal risks (parks and reserves). Desperate actions required to address food crises or famine can lead to displaced populations and emergency actions that have environmental consequences. Finally, food security provides the foundation required for effective outreach and learning about systematic approaches to improving natural resource management.

The three-way nexus between resource management, bioenergy sustainability, and food security

The interactions between these three factors form the central region of the Venn diagram in Fig. 3. Good governance incorporates both political commitment and the institutional capacity to provide effective services and security under the rule of law. Good governance is essential for effective resource management, food security, and bioenergy sustainability. Government institutions provide 'social safety nets,' or create conditions that allow nongovernment organizations to fill this role, to help vulnerable populations cope in times of food crisis. These coping mechanism become unavailable or inoperable when governance fails or is undermined by corruption. Several initiatives promoting sustainable bioenergy (e.g., GBEP, 2011; RSB, 2011; FAO, 2011a) acknowledge this nexus by considering governance, participation of civil society, and development of institutional capacity.

Respect for peoples' rights to land and resources is interwoven with good governance and prerequisite for any project promoting more sustainable production (FAO, 2011a; Dale *et al*., 2013). The 'Global Commercial Pressures on Land Project' found that failures of governance were causal factors leading to 'land grabs' (Anseeuw *et al*., 2011). Traditional uses of land and other natural resources by the poor are of special concern when designing policies and projects to enhance food security. Guidelines are available to ensure that biofuels development takes traditional land rights into consideration (e.g., FAO, 2011a, 2013b). Properly applying these guidelines would avoid problems such as the displacement of smallholder farmers by agro-industrial developments as transpired in Colombia (Clancy *et al*., 2013).

Investments in infrastructure and advances in technology are necessary for all parts of the system. Food security requires the means to produce, package, and distribute high-quality food. Biofuel sustainability relies on efficient systems for production, transport, and processing. As documented in Brazil, investments in bioethanol industries can support spin-off benefits for neighboring productive sectors and local economies. In rural areas where biomass and labor are abundant, but infrastructure is limited by lack of funding, bioenergy investments help fill gaps and facilitate economic development (Batidzirai & Johnson, 2012; Moraes & Zilberman, 2014). In Malawi and Tanzania, contracting with smallholders was found to effectively improve household incomes and community welfare (Sulle & Nelson, 2009; Hermann & Grote, 2015).

Integrated crop management and production systems are necessary for efficient provision of food, feed, fiber, and energy feedstocks. Integration helps minimize use of inputs such as fertilizer or pesticides and helps optimize use of assets such as natural, social, physical, and financial capital (e.g., Pretty, 2008; and Mueller *et al*., 2012). Combining the goals of food security and biofuel sustainability with other local priorities contributes to increases in total factor productivity that are responsible for the majority of growth in output from global agricultural systems over the last decade (Fuglie & Rada, 2013). Integrated system design can also help to identify opportunities to utilize what might otherwise be considered waste from one part of the system, as input for other parts (Berndes *et al*., 2015). Reduction in and reallocation of waste offer significant benefits, particularly if the waste would otherwise be burned or require costly removal.

Diverse ecosystem services are influenced by the interactions among resource management, food, and biofuel feedstock production (Gasparatos *et al*., 2011). For example, enhanced water and air quality, improved soil conditions, stable jobs, and economic benefits can all accrue if the agricultural system is designed and deployed in a way that efficiently meets the demand for food, fiber, and feedstocks (Berndes *et al*., 2015; Souza *et al*., 2015).

The occurrence of extreme weather events is unpredictable, but their intensity and frequency are expected to increase because of climate change (IPCC, 2014). Resilience to extreme events is enhanced through diversified production systems and multiple suppliers with flexibility to adjust based on the linkages between resource management, food security, and sustainable bioenergy production systems. This buoyancy can occur whether the disturbance is due to natural events (e.g., hurricanes, droughts, fires), market forces (e.g., sudden sharp decline or rise in prices), or human-induced disasters (social or political conflicts). More diversified production systems have also been shown to be more adaptable to change than traditional monoculture production systems (Woods *et al*., 2015).

By understanding the nexus and intentionally designing systems to promote beneficial linkages among resource management, bioenergy sustainability, and food security, we can enhance the resilience and adaptability of biofuel and food production systems and the coping mechanisms required in times of crisis. Such integrated systems should be designed to apply best practices and support critical local priorities including food security (Tables 4 and 5).

Priorities and conditions to achieve positive synergies

Many challenges in reconciling bioenergy and food security also present opportunities. Achieving positive synergies between bioenergy and food production requires science-based clarifications about context-specific problems. This also demands science-based validation of assumptions and clear definitions. Therefore, in addition to techno-economic challenges of multiproduct agricultural systems, we also should resolve barriers to social acceptance, clarify terminology, and verify that

Table 5 Benefits arising from the systemic integration of food production and bioenergy (based on Dale *et al.*, 2014, and case studies cited in this paper)

Main principle	Land-efficient food production and consumption	Integrated bioenergy production and use	Comments
Food security	Increased food supply, decreased pressure on land	Direct provision of energy services and income from existing land	Enhanced coping capacity also essential; requires planning for optimized use of limited resources (capital, water, inputs, time)
Climate security	Reduced land clearing and land-use change	Supply of low-carbon energy to agriculture and rural communities	Enhanced soil and above-ground carbon stocks; increased resilience
Energy security and supply	Increased land for bioenergy and ecological habitats	Increased provision of local energy services	Bioenergy providing low-cost drying, processing energy, and transport energy
Preservation of habitat, wild places	Reduced expansion of managed lands	Enhanced vegetation cover, species diversity, and wildlife corridors	Introduction of perennial cropping in riparian zones, on steeper slopes and in vulnerable zones in water catchment
Enhanced soil quality	Increased resiliency and crop yields	Benefits of perennial bioenergy crops in landscape and cropping strategies with greater diversity of options	Novel crop rotations, increased use of perennials to enhance soil organic matter and reduce soil disturbance
Enhanced environmental quality	Increased intensity of production with reduced environmental impacts	Novel landscape planning and cropping strategies to reduce erosion, enhanced nutrient and water availability, and decreased leaching	Benefits not a default outcome but will require careful planning and implementation combined with improved extension, knowledge transfer, and IT-based decision tools
Poverty alleviation	Greater and more resilient yields, reduced storage losses, and improved tillage and transport logistics raise income and reduce economic losses	Enhanced reliability and resilience of local energy supply; hedging strategies provided in case of damaged, condemned, or contaminated crops; improved use of residues to raise income	Direct benefits to rural farmers, processors, and traders. Care required with emerging economies of scale and marginalization of the most vulnerable/poor
Rural economic development	Increased competitiveness, enhanced knowledge and innovation capacity	Increased local economic activity and critical mass	Benefits to urban poor and rural poor

scientifically sound approaches are applied to address real problems. Focusing on positive synergies urges us to ask the right questions and to identify mechanisms for energy investments that improve food security.

Use accurate and consistent terms for analysis and communications

Robust scientific analysis should be grounded in a clear definition of the problem to be assessed and a systemic approach to resolving it. The results of many studies rely on faulty assumptions such as: Global land area is the limiting factor for food production; producing more commodities in the United States will alleviate global hunger; or any increase in commodity prices will cause food insecurity. Furthermore, policymakers and the public are misled by terms used in reporting research about food security. For example, #2 yellow corn, the subject of many reports about U.S. biofuel impacts on 'food security,' is a feed grain unfit for direct use as food. U.S. maize grown for human consumption (sweet corn, white corn, popcorn) represents about 3% of total U.S. corn production (Hansen & Brester, 2012), and from 2010 to 2014, represented only 2% of total U.S. maize exports (USDA-GATS, 2015). Simplified models confuse #2 yellow industrial feed with food. Resulting communications promulgate misconceptions, for example, that food insecurity increases with increasing commodity prices of corn or sugar (Table 3). Authentic communication requires that appropriate terminology is defined clearly and used consistently.

Recognize that food and bioenergy need not compete for land

The idea that bioenergy competes with food for land is predicated on several correlations and assumptions, beginning with land being a limiting factor for global food production. The land scarcity concept is based, in part, on conventional wisdom ('Buy land, they aren't making more of it!') and on an oversimplified interpretation of historical land clearing. Many analyses assume incorrectly that a land-cover class indicates the cause of clearing. In such analyses, forest cover typically change to agricultural cover classified as crops or pastures, and deforestation is attributed to agricultural demand. Yet, when viewed from social and historical perspectives, the actual causes of deforestation can be attributed to many other drivers such as colonization and tenure policies, market-distorting subsidies, speculation based on intrinsic value, new infrastructure, customary practices for claiming frontier land, migration, and extractive enterprises (Scouvart *et al.*, 2007; Kline & Dale, 2008).

Sorting out complex causal relationships for deforestation is difficult (Pacheco *et al.*, 2012). Quantitative models are facilitated by the convenience of remote sensing data and the simplicity of the conventional assumption that causation can be determined by the apparent land cover following deforestation; however, oversimplifications in such models often lead to faulty conclusions (Dale & Kline, 2013). Correlations between deforestation and increasing 'agricultural area' are assumed to reflect agricultural land scarcity. Several studies that use models to support the hypothesis that biofuels compete globally for land with food (Boddiger, 2007; Tenenbaum, 2008; Searchinger & Heimlich, 2015) rely on assumptions that contradict empirical evidence (Kline *et al.*, 2011; Souza *et al.*, 2015).

Indeed, policymakers in major food-producing nations have been challenged by waste, overproduction, and depressed farm-commodity prices for decades. As a result of excess production, policies were developed in the 1980s and 1990s to reduce spoilage, waste, and financial losses associated with excessive stocks of major food commodities. Those policies emphasized land set-asides and environmental protection rather than increased production. Furthermore, food security in some less developed nations was impaired by food 'aid' and subsidized export of surplus production (Thurow & Kilman, 2009; FAO, WFP, 2010). Since the 1990s, innovations in technology, system integration, and logistics have allowed producers to meet the growing global demands for food without requiring additional land (Alexandratos & Bruinsma, 2012; Conway & Wilson, 2012). Yet the belief that biofuel production directly competes with food production and increases food prices remains widely held (e.g., Hajkowicz *et al.*, 2012).

It becomes clear that global land area is not the limiting factor for food and bioenergy production when consistent data on land cover, land use, and productive potential are applied to the analysis (Babcock, 2011; Woods *et al.*, 2015). Despite ongoing population growth and deforestation, the total land area *used* to feed the world has remained steady since 1990 (Ausubel *et al.*, 2013; FAOStat, 2015). The average area of cropland used to feed one person has fallen from 0.45 ha in 1961 to 0.22 ha in 2006 (FAO, 2011b) and is projected to be close to 0.19 ha at present, based on FAOStat 2015. At 0.19 ha per capita, 1.7 billion hectares, or about a third of all arable land available today, could feed the population of 9 billion projected for 2050.

Output from most agricultural land is far below potential yields (Mueller *et al.*, 2012). Thus, the land *required* to feed humanity is a fraction of that currently classified as agricultural (Woods *et al.*, 2015). Most U.S. cities could be fed from a 50-mile-radius 'foodshed'

(Zumkehr & Campbell, 2015). Rooftops and other small urban gardens illustrate that far higher yields per hectare are possible, potentially reducing land *requirements* to as little as 0.01 ha per capita (Orsini *et al.*, 2014; Rockwell, 2015). Still less land would be required for intensive, closed-loop agricultural systems that recycle water and nutrients. Given current trends, some researchers expect that the agricultural area required to support global food needs will decline over coming decades (Roser, 2015).

When considering land, context is critical. Local competition for land reflects historic inertia and can be politically and socially sensitive. Even though no further deforestation is required to feed humanity well into the future, deforestation continues due in part to poor understanding of the local causes. Effective policies to conserve natural areas do not require reducing food or biomass production but may involve incentives for efficient resource management and recycling of water and nutrients.

Invest in technological innovation to build capacity and infrastructure

One of the most persistent recommendations for improving food security is to invest in rural agricultural technology, as discussed in the SOFI reports and reflected in multiple recent initiatives to ‘feed the future’ (Godfray *et al.*, 2010; IMF, 2013; USG, 2015; World Bank, 2015). However, during periods of historically low real prices for food producers, there is limited motivation for investments in technology or yield improvement. Declining support for agricultural research around the globe since the 1970s is a concern, and the ‘significant decline in annual investment in high-income countries between 1991 and 2000 is especially troubling’ (Beachy, 2014). Case studies in Brazil have illustrated the potential for investments in bioenergy technology and infrastructure to simultaneously reduce hunger, expand food commodity exports, and promote socioeconomic development (Souza *et al.*, 2015).

Investments in innovation and local infrastructure are promoted at the nexus of sustainable bioenergy, food security, and resource management. Innovations in technology and integrated production systems characterized recent biofuels expansion in the United States and Brazil (Gee & McMeekin, 2011). Bio-based industries that can entice new investments are a prominent part of many rural development strategies (UNCTAD, 2014). Investment is required to complement the land and labor that tend to be plentiful in rural areas at risk to food insecurity (FAO, 2015a). Key constraints, capital and technology, can be alleviated by investments in strong, growing markets.

Promote stable prices high enough to incentivize local food production

Price volatility in a food security context is defined as large, sudden changes in the prices of staples on which at-risk populations depend. Sudden price increases make staples less accessible to urban at-risk groups, while sudden decreases undermine smallholder producers’ livelihoods and household incomes in rural areas. More predictable staple prices that create incentives for local investment in food production are important to improving food security (IFPRI, 2015). Declines in prices are more detrimental to food security than temporary price spikes because (1) capacity and investment in local food production supply chains are undermined, (2) over 70% of the global population living with hunger is in rural areas (FAO, 2014, 2015b), and (3) price crashes catalyze rural-to-urban migration, which can further undermine existing productive capacity. Rural areas and uncharted neighborhoods created by recent migrants are more difficult and costly to reach with food assistance than well-established, urban populations. Farmers and agro-industries have demonstrated capacity to respond to local market signals for products that can be grown profitably.

Adopt flex crops that can provide food and other products

Extreme weather events such as drought and flood are inevitable and cause unpredictable supply shocks in affected areas. Trade combined with surplus production from diverse regions can help alleviate such vulnerabilities to extreme events. Remote sensing tools and communication platforms that share crop progress and projected harvest data are increasingly allowing far-flung regions to respond quickly to supply shocks. Producers with competitive technologies and access to markets can boost yields or plant a second crop on existing fields. The supply shock caused by the 2012 drought in North America was offset in part by planting second crops on existing fields in the Southern Hemisphere (USDA, 2013). The increasingly interconnected world is better informed and responsive to arising crises, helping to reduce casualties from famine over the last two decades (Roser, 2015).

Biofuel markets have been proposed as one mechanism that can absorb the surplus production in normal years and provide a cushion in years of unexpected supply disruptions. The opportunities offered and problems created by ‘flex crops’ that can serve food and other markets merit further study. International organizations concerned with food security (e.g., FAO, IFAD, IMF, OECD, UNCTAD, WFP, the World Bank, WTO, IFPRI) support policies or market mechanisms that allow feedstocks to be diverted from biofuel production to uses that could dampen volatility of food commodity prices (see for example the Committee on Food Security report, HLPE 2013; Locke *et al*., 2013). This ability to shift end use of available supply as a 'safety valve' to reduce price volatility (Wright, 2011) has been a cornerstone of Brazilian strategies for maintaining strong biofuels and sugar industries (Osseweijer *et al*., 2015).

Similarly, U.S. maize production capacity expanded from 2002 to 2011 in part as a response to federal biofuel mandates. Investments made during this period in technologies such as precision agriculture, irrigation, and grain storage would have been impossible without favorable profit margins. Federal support to expand biofuel markets increased confidence in the ability to sell crops at a profit. The investments increased efficiency and reduced long-term production costs. Investments in irrigation and storage between 2002 and 2012 also helped to moderate price volatility in the face of the worst drought to hit U.S. farms in more than 50 years (USDA, 2013). A drought of this magnitude represents a 'supply shock' that could have triggered a global food price crisis, but market responses helped avoid a major price spike. Moreover, the drought and its effects were monitored and communicated widely, which allowed Southern Hemisphere nations to respond with second crops of maize. There is growing recognition of the value of flex crops combined with good market intelligence to support predictable and relatively stable commodity prices, as this information influences decisions of buyers and sellers in futures markets (FAO-UNEP, 2011; UNCTAD, 2014).

Identify conditions under which bioenergy improves food security

Integration of land- and resource-efficient food and bioenergy production will increase the sustainability of the system and extend benefits across multiple value-added product chains (Table 5).

Conclusions and recommendations

Relationships among food security and biofuel policies are complex and context specific. Such nuanced local relationships cannot be captured in global-scale analyses, and the validity of simple models for useful policy guidance is questionable. Assessing impacts requires an understanding of the interactions among factors relevant to food security within a specific place and time. The debate needs to transition from irreconcilable generalizations about whether biofuels are 'good or bad' for food security, to constructive understandings of where and how biofuels can help achieve sustainable development goals including the eradication of hunger. The following recommendations aim to facilitate synergies between food security and energy security through careful planning and development of bioenergy projects and policies.

Ask the right questions

Analysis must consider local contextual conditions to understand the drivers of food insecurity. Multiple causal factors should be addressed using a holistic approach. Developing a bioenergy policy or project designed to improve food security requires that answers to the following questions be applied to a well-defined, local context.

1. Who is most at risk from food insecurity?
2. What factors are causing or increasing the risk of specific food security problems? How do these factors relate to energy and fuels?
3. What actions are feasible and likely to effectively address the causal risk factors?
4. What can be done to mitigate hunger problems in the near term while also building resilience to reduce future risk of food insecurity? And how do these actions and those identified in response to question 3 relate to potential (bio)energy/fuels?
5. How can a bioenergy policy or project be designed to address the local causal risk factors and contribute to reduced food insecurity?
6. Is a regional development plan that integrates sustainable bioenergy more effective and efficient in achieving food security goals than one without bioenergy?

Engage stakeholders to address needs for food and energy security

Consensus-based principles of sustainable global food security underscore the importance of developing projects with local ownership that consider the needs of the most vulnerable populations (FAO, 2015a) (Table 4). Stakeholders can help identify ways in which bioenergy investments can reinforce efficient local food production and other services. Stakeholder engagement also supports adaptive decision-making to enhance goal achievement (Dale *et al*., 2015).

Encourage coproduct complementarity, diversity, and stable markets

Relatively stable and predictable prices for food and energy are essential for food security. Access to affordable energy supports food security goals, while energy price volatility can exacerbate food crises. Building confidence with long-term policies allows markets to work effectively. For example, to the degree that biofuel policies support a more stable and profitable market-driven price floor, local production can be incentivized by markets that can absorb increasing output. If price caps are used to protect consumers, mechanisms to support local producers may be needed lest food security be undermined. As price crashes are often more detrimental to long-term food security than price spikes, sudden shifts in policies that reduce investment in agricultural production should be avoided.

Diversifying sources of production and end uses of agricultural products enhances local food security. More efficient production of nutritious staples can be promoted through integrated production systems that offer a diversity of coproducts for bioenergy and other markets. Crops that can serve multiple markets reduce risks for producers and possibly enhance food safety by providing noon-food outlets for contaminated or damaged food. It may be beneficial to promote strategic supply chains in order to facilitate access to multiple markets for such 'flex crops.' Investments in better technology and more efficient production (e.g., precision agriculture and efficient irrigation) can help producers respond to market signals for different crops as well as adapt to disturbances such as those caused by weather. Diversity in the geospatial distribution of production and types of production can reduce price sensitivities caused by disruptive events (e.g., political upheaval, flood, or drought).

Support planning and implementation of landscapes designed for multiple uses and waste minimization

Apply landscape design to help stakeholders assess trade-offs when making choices about locations, types, and management of crops, as well as transport, refining, and distribution of products and services. Landscape design refers to a spatially explicit, collaborative plan for management of landscapes and supply chains for food, energy, and other services (Dale *et al.*, 2016), which respects traditional landholdings and farming practices. Proactive resource-use planning can support improvements in management and provision of services based on a set of defined goals (Dale *et al.*, 2014). Such planning should consider shared infrastructure to meet the needs for food, energy, and other markets in a way that reduces costs and waste. Reduction in agricultural wastes provides a means for more efficient crop production. Agro-ecological zoning developed in response to biofuel sustainability concerns in Brazil has influenced other agricultural sectors and helped protect biodiversity and forests, which are important sources for sustained food production in rural areas (Sunderland *et al.*, 2013). The sugarcane–ethanol industry in Brazil supports 4.5 million jobs, improves livelihoods, and promotes rural infrastructure and development (Moraes & Zilberman, 2014).

Apply adaptive management and promote continual improvement

Adaptive management involves learning from ongoing monitoring so that decisions can be adjusted to changing conditions and needs. Timely information about environmental, social, and economic conditions, local crops, and market intelligence can support more sustainable food and energy production. It is important to collect data and monitor indicators of food and energy security that are most relevant to local context and stakeholders. Local monitoring helps to verify progress, flag problems, and signal requirements for corrective actions. The information gained needs to inform adjustments in management practices and plans that support adaptation to changing conditions. Accurate and timely data on prices, stocks, futures markets, and weather are essential to support monitoring and adaptive management. Crop monitoring and timely information sharing can also help address unplanned supply shortfalls and reduce price volatility, as observed when Southern Hemisphere nations such as Brazil and Argentina planted second crops in response to early reports of the 2012 U.S. drought.

Communicate clearly about barriers and opportunities to address local needs

How food and food security are discussed shapes public opinion. Clear definitions, consistent use of terminology, science-based problem identification, and validation of assumptions help reduce confusing and conflicting messages. Data need to be relevant; communications focusing on global commodity prices may have little bearing on the factors that determine when and where local food insecurity becomes a problem. Reliance on readily available aggregate data distracts attention from aspects of food insecurity that matter most for peoples' health and well-being. Timely information on the status of indicators for environmental, social, and economic effects of development projects needs to be publicly accessible. Long-term commitments to food security, energy security, and environmental quality need to be broadly communicated, and defined goals should be shared widely.

Collaborate with local development programs on common goals

Bioenergy policies can support progress toward the 2030 Sustainable Development Goals of doubling of agricultural productivity, improving incomes of small-scale food producers, and providing clean energy for all (UN, 2015). Research should provide relevant lessons drawn from bioenergy−food interactions over the last decade to guide efforts to provide food and energy while reducing greenhouse gas emissions (Dale *et al*., 2011). The 2015 assessment of progress toward Millennium Development Goals (MDGs) found that several countries with domestic biofuel production policies, such as Brazil, China, Indonesia, Malawi, Malaysia, and Peru, also achieved or exceeded challenging hunger-reduction goals (FAO, IFAD, WFP, 2015a). Other countries with notable bioenergy potential, but where biofuel policies were not effectively implemented, such as Zambia, Senegal, and Guatemala, fell short on MDG hunger-reduction targets (Tay, 2013; Mukanga, 2014; UNCTAD, 2014; World Bank, 2015). Biofuel projects responsive to site-specific needs in developing nations offer opportunities to support food and energy security goals (Kline *et al*., 2009; Gasparatos *et al*., 2011; Mitchell, 2011).

Build on and improve existing systems

Bioenergy is already an integral part of global food production, processing, and consumption systems. Experience indicates that investments in bioenergy can help expand local food supplies, infrastructure, and productive capacity and thereby reduce risks of hunger for specific groups and situations (FAO, 2011a; Durham *et al*., 2012; Moraes & Zilberman, 2014). The nexus of bioenergy, food security, and resource management is especially significant for the rural poor. Dependence on subsistence agriculture and inefficient traditional biomass use leaves rural populations vulnerable and deepens impoverishment through resource degradation. Current practices can transition and transform through continual improvements to meet the needs of society in a changing world. Institutional capacity for learning and sharing experiences should be developed across the supply chain. Applying science to support continual improvement will help feed more people and provide them with more sustainable energy resources for the future.

Prioritize research investments

Future research priorities include better monitoring and analysis to determine cause-and-effect relationships among factors that determine vulnerabilities to food insecurity. Research should support design and planning so that negative effects are minimized or avoided and persistent improvements in energy and food security are achieved. Better resource management can address both food and energy needs and lift people out of poverty, but this requires governance and policies that create the right incentives. Case studies that document actual conditions before and after project implementation can support more integrated project designs and adaptive management (FAO, 2011a; Elbehri *et al*., 2013). Transparent documentation of the problem, hypotheses, research methods, input data sources, and assumptions is essential to avoid potential misrepresentation of analytical results (Dale & Kline, 2013).

Conclusions

Effectively addressing food security and bioenergy sustainability requires a renewed focus on populations at risk. Understanding the local causes of food insecurity is a prerequisite step for designing bioenergy projects that improve food security in a specific place and time. This approach requires multidisciplinary analysis and program design to consider and address key constraints and opportunities. Projects should target rural poor with opportunities to engage in more sustainable, diversified, and integrated systems that provide clean, affordable fuels and nutritious food. Bioenergy can contribute to improved food security through production systems designed to increase adaptability and resilience of human populations at risk and to reduce context-specific vulnerabilities that could limit access to local staples and required nutrients in times of crisis.

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