



Original Article

Responding to Global Challenges in Food, Energy, Environment and Water: Risks and Options Assessment for Decision-Making

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Abstract

We analyse the threats of global environmental change, as they relate to food security. First, we review three discourses: (i) 'sustainable intensification', or the increase of food supplies without compromising food producing inputs, such as soils and water; (ii) the 'nexus' that seeks to understand links across food, energy, environment and water systems; and (iii) 'resilience thinking' that focuses on how to ensure the critical capacities of food, energy and water systems are maintained in the presence of uncertainties and threats. Second, we build on these discourses to present the causal, risks and options assessment for decision-making in the presence of risks. The process provides a structured, but flexible, approach that moves from problem diagnosis to better risk-based decision-making and outcomes by responding to causal risks within and across food, energy, environment and water systems.

Key words: food security, sustainable intensification, nexus, resilience, sustainable development, sustainable development

1. Introduction

Sustainably feeding more than 9 billion people in 2050 is arguably the largest global challenge over the next 35 years (Grafton et al. 2015b). Not only will food production need to increase by at least 50 per cent (FAO 2014) but also, on current trends, a similar upward trajectory is foreseen for essential inputs to the food system. Without a fundamental shift in production processes, a projected 55 per cent more water (WWAP 2014) and 40 per cent more energy (IEA 2014) would be required to support future food demands (UNDESA 2013). Such rising demands would occur in a world where agriculture already accounts for some 70 per cent of surface and groundwater withdrawals (AQUASTAT 2015) and roughly a third of the planet's land surface area (Foley et al. 2003).

To meet the global food security challenge to 2050, we cannot simply rely on the methods used to triple food production over the past 50 years. The intensification of food production since the 1960s has been a great success in reducing global hunger (Evenson & Gollin 2003), but the methods and policies driving

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success frequently lacked incentives for prudent use of inputs (Pingali 2012). The unintended legacy of this period of agricultural and economic development has been a loss of biodiversity and forests, deterioration of soil, water and air quality, closed river basins, deforestation and desertification (Grafton et al. 2013; Laurance et al. 2014; Matson et al. 1997).

Evidence suggests that past environmental degradation has weakened the resilience of agro-ecological systems (World Bank 2013) and may also have contributed to a slowing in the rate of crop yield growth since the 1980s (Barrett 2010; FAO et al. 2014; Pingali 2012). We argue that the policy and management of complex food production systems must be reconsidered, particularly in relation to how critical inputs such as land, water, energy and nutrients are used. We must also consider risk more explicitly when evaluating policies and investments, given the likelihood of spatial and seasonal changes in temperature and rainfall, due to climate change, and the potential impacts on crop, livestock and fish production.

The vulnerability of key food, energy and water systems to the current trajectory of resource use trends has been called the 'perfect storm' (Beddington 2009). A growing awareness of the capacity for adverse shocks to proliferate through linked systems, or 'systemic risks' (De Bandt & Hartmann 2000), has coincided with a focus on resource security and risk-based principles for decision-making under uncertainty (Hall et al. 2014; Paté-Cornell 2012). The global challenge is to confront these systemic threats through resilient, sustainable, risk-based decision-making that responds to uncertainties and creates options to sustainably feed the world (WEF 2015).

Here, we address what we believe to be the critical obstacle to accomplishing the sustainable development goals that will frame the global agenda in the coming decades: ensuring that global food security is equitably achieved for a much larger projected population, without causing a cascade of negative impacts on the water, energy, climate, land and environmental systems needed to support food production.

First, we use examples from across the globe to illustrate the threats associated with global environmental change. Second, we examine three discourses ('sustainable intensification (SI)', the 'nexus' and 'resilience thinking') that have been proposed as approaches to respond to food, energy and water threats. Third, we introduce a new approach to decision-making that builds on key aspects of the three discourses while explicitly addressing risk: the risks and options assessment for decision-making (ROAD). This process is a structured, but flexible, approach for assessing causal risks within and across food, energy, environment and water systems. We conclude by highlighting the importance of testing and applying the ROAD process in multiple landscapes and circumstances.

2. Global Food Security Threats

Food security is a multi-dimensional concept (Warr 2014) that includes the following: (i) physical *availability*, which involves the food production, stocks and reserves across multiple scales; (ii) economic and physical *access* that are dependent on incomes, food prices, infrastructure and markets; (iii) food *utilisation*, or the capacity to absorb nutrition according to health, diet diversity and intra-household distribution; and (iv) *stability* of the other three factors over time, despite transitory shocks or periodic stresses (FAO 2008).

Achieving food security at the household, community or national level is more complicated than simply ensuring that aggregate global food supply meets global food demand. It is deeply connected to the ownership of resources and assets (particularly land), and the capacity of individuals and communities to acquire goods and services with those endowments (Sen 1981). Achieving food security requires strong institutions, effective policies and financial resources to improve access to markets, health services, infrastructure and not just an increased food supply. Importantly, strong institutional arrangements are needed along the entire food supply chain to ensure the 'system' works effectively from the beginning to end (Qureshi et al. 2015).

All three of these issues—strong institutions and effective policies, meeting short-term needs sustainably and the importance of poverty and equity—point to food security as key to achieving sustainable development. This connection is exemplified by the sustainable development goals. In addition to the hunger, food security and sustainable agriculture goal, all 16 of the other goals, such as ending poverty, ensuring health and well-being, the availability and sustainable management of water and sanitation and protecting ecosystems, directly or indirectly support the different dimensions of food security (UN 2015). The sustainable development goals will set the post-2015 aid and development agenda, as sustainable food production and consumption systems are necessary conditions for current and future global food security (Alder *et al.* 2012; Godfray *et al.* 2010; Searchinger *et al.* 2014; Tilman *et al.* 2011; WEF 2010).

Achieving future global food security is complicated by the interdependencies and distributive trade-offs between food, energy, water and natural resources. For instance, agriculture is responsible for more than two-thirds of global freshwater withdrawals (AQUASTAT 2015) while accounting for 30 per cent of global primary energy use along its value chain (FAO 2014). In addition, agriculture uses more than one-third of the global land area not under permanent ice cover (Foley *et al.* 2003; FAO 2015).

Recent anthropogenic pressures have further entangled resources (Dobbs *et al.*, 2011; Ringler *et al.*, 2013), exposing new vulnerabilities and systemic risk in a ‘hyper-connected’ world (Helbing 2013; WWF 2013). For example, hydro-climatic variability and socio-economic change are connected at multiple geographical scales (Veldkamp *et al.* 2015). A global push for biofuel production, for instance, has intensified competition between food and energy production for land and water resources (Havlik *et al.*, 2011; Rosenzweig *et al.* 2014) and contributed to millions becoming undernourished during the food price spikes of 2007–08 (Dalla Marta *et al.* 2015; To *et al.*, 2015). Another example of acute trade-offs is the planning for new hydropower

dams in the Lower Mekong Basin. The 11 dams planned for the Mekong River, and 78 planned for tributaries, are projected to reduce by about half the biomass of migratory fish species by 2030 (Ziv *et al.* 2012), thus causing a major loss in food protein produced in the region (Orr *et al.* 2012).

In interdependent systems, the failure of a single element may result in a ‘catastrophic cascade of failure’ (Buldyrev *et al.* 2010), with international repercussions (Goldin & Mariathan 2014). This is true of global food systems—and the policies and processes that govern them—that are increasingly vulnerable to the challenges presented by global environmental change (Ericksen 2008; Krishnamurthy *et al.* 2014) and the Anthropocene (Crutzen 2002; Steffen *et al.* 2015).

Assorted environmental, political, economic and demographic trends are emerging over various temporal scales, causing threats to systems that support the different dimensions of food security (Hoddinott 2014). Here, we briefly review rapid, slow and prolonged threats to global food security and the implications for decision-making scales.

2.1. Rapid Onset Threats

Rapid onset threats are characterised by their sudden occurrence. Examples include the recurrent floods in Pakistan that have occurred since the unprecedented flooding in 2010 that displaced 18 million people and damaged crops worth \$2.2 billion (Dorosh *et al.* 2010; Zselezky & Yosef 2014). In subsequent years, monsoonal flooding has been increasingly extreme and unpredictable (UNHCR *et al.* 2014). These repeated flooding threats have undermined recovery, eroded the resilience of people and food systems and lowered economic growth (FAO 2015).

Extreme temperatures can impair household and national food supplies. For example, livestock is vulnerable to heat stress that raises their susceptibility to parasites and can negatively affect meat quality and weight gain. Reductions in the number of flowering days can slow plant growth and reduce the yield of annual and permanent crops. Temperature stress

can cause blemishes on fruits and vegetables while reducing proteins, vitamins and fatty acids (MSSI 2015).

Food price volatility is another rapid onset threat to global food systems, as demonstrated in 2007 and 2008, when several global trends (Allouche 2011; de Gorter et al. 2013; Headey & Fan 2008; Royal Society 2009) rapidly intersected to cause food price rises unprecedented in scale since the 1970s (Torero 2012). The global impact was substantial: riots and demonstrations in more than 50 countries (Allouche 2011); political upheaval in Haiti and Madagascar (Brinkman & Hendrix 2011); and an additional 60 million people undernourished around the world (Tiwari & Zaman 2010).

2.2. *Slow Onset Threats*

Slow onset threats unfold over years, as societies and environmental systems approach key thresholds. The transformation of diets in Eastern Asia is a prominent example. The increasing demand for meat consumption among the large and growing middle class in China is creating pressures on land and water resources to supply more animal feed (Veeck 2013). These shifts are generating a slow onset threat to the global food system. Failures of policy to respond to such threats were exemplified in 2011 when China lifted restrictions on the import of soy products for cattle feed, triggering expansion of Brazil's soybean production, with negative consequences for deforestation of the Amazon and impacts on the local water cycle (Dalin et al. 2012). The globally increasing demand for palm oil is generating another slow onset threat, wherein policy failures have contributed to deforestation in Indonesia (Sanders et al. 2013). This, in turn, contributes to future global climate effects through the loss of significant carbon regulating services (Kessler et al. 2007; Satriastanti 2014).

A drought can be either a slow or rapid onset threat, depending on its magnitude and duration. The droughts in Russia in 2010 and China in 2011 triggered global food security threats that were exacerbated by maladapted policy interventions (Zseleczy & Yosef 2014). In

Russia, for instance, export bans contributed to a rapid increase in global food prices (Wegren 2011). In China, the purchase of wheat from the global market by the Chinese government greatly increased wheat prices and was, in part, responsible for the civil conflict in Egypt (Sternberg 2012).

2.3. *Prolonged Onset Threats*

Prolonged threats are those that develop over decadal or multi-decadal timeframes, affecting multiple systems and contributing to the development of slow-onset and rapid-onset threats. Climate change exemplifies a 'prolonged' threat (Hoddinott 2014) that can reduce global crop yields, over time, in the absence of adaptation (Wei et al., 2009) and increase production uncertainty and vulnerability from one growing season to the next (Gornall et al. 2010; Conway & Schipper 2011; Müller & Robertson 2014; Rosenzweig et al. 2014).

South Africa illustrates the causal risks and challenges when responding to prolonged threats. This country's stationary energy sector depends heavily on fossil fuels and is a significant contributor to national greenhouse gas emissions. Projected climate change in much of South Africa is expected to reduce water availability for crop and livestock production. Yet to insulate themselves from adverse climate variability and change, some farmers have responded by adopting more energy-intensive irrigated agriculture (Carter & Gulati 2014). Such perverse responses are replicated in many other countries, including Australia (Mushtaq et al. 2015; Wheeler 2014).

2.4. *Decision-making Agents and Scale*

Threats manifest themselves differently across decision-making scales. The available responses are different for farmers, communities, firms and policy-makers, seeking to control risk or mitigate negative consequences. Equally, the responses deployed by different decision-makers can affect many stakeholders, and there may be trade-offs between the winners and losers from both the consequences and responses associated with a threat. In the

examples in Table 1, we illustrate how threats in vulnerable river basins generate different consequences across multiple scales. Crucially, these differences across spatial, temporal and socio-political scales are what make risk-based decision-making so challenging.

The rapid, slow and prolonged threats we summarise in Table 1, across household, community, national and regional scales, motivate our development of the risk-based ROAD process described in Section 4. Smallholder farmers and their families face increased risks to their crop and livestock production activities. Greater variability in yields, due partly to climate change, increases the pressure on smallholder households to generate higher income, but at the risk of greater risk of malnutrition should their strategies fail. Public officials, in turn, need to determine the investment strategies that minimise the most salient risks while optimising the use of limited investment funds.

National and regional authorities need to utilise risk assessments to effectively prepare for and respond to rapid, slow and prolonged onset threats (Table 1). Higher food prices or reductions in crop yields can have near-term and negative impacts on household and national food security, while sustained declines in agricultural productivity and farm incomes may threaten livelihoods and cause extensive slippage into poverty and food insecurity. Sea-level rise, coastal erosion and the persistent overdrafting of aquifers can result in substantial economic harm, possibly requiring large-scale migration in some countries. The public costs of alternative interventions to prevent or delay the onset of such outcomes must be evaluated in light of the likelihood of such outcomes occurring, and in their particular circumstances and settings.

3. Three Discourses on Food Security and the Environment

Over the last decade, three discourses that have relevance to food security have emerged from or have been influenced by the field of ‘sustainability science’ (Kates et al. 2000; Kates & Dasgupta 2007; Jerneck & Olsson 2014;

Prosperi et al. 2014): ‘SI’, the ‘nexus’ approach and ‘resilience thinking’ (Walker & Salt 2006; Béné et al. 2011; Biggs et al. 2015; Sellberg et al. 2015). Each discourse describes a different response and approach towards achieving food security while better managing the long-term integrity of critically important water, energy and environmental systems.

We analyse the key tenets of these discourses with a view to identifying the strengths and limitations of each in achieving global food security goals. We synthesise their insights in Section 4.

3.1. Sustainable Intensification

Sustainable intensification has focused on production efficiency in addressing food security challenges. It places an emphasis on getting ‘more from less’: increasing agricultural yields without adverse environmental impacts or additional cropland cultivation (Royal Society 2009). SI has been interpreted by some scholars as requiring a radical rethinking of agricultural systems (Godfray 2015) and repositioning the global agricultural system from a negative driver of environmental change to an important contributor to efforts to live within sustainable planetary boundaries. Others suggest that the notion of SI is unclear and perhaps does not reflect a substantial difference from current production practices (Petersen & Snapp 2015; Wezel et al. 2015).

3.1.1. Application

The strength of SI lies in the variety of farming strategies that can be selected to suit the contextual challenge (Godfray 2015). Supply-side solutions are politically palatable, arguably easier to implement and have typically been fostered by single-sector perspectives founded in the science and technology that delivered past production increases. In Africa, for example, the introduction of low tillage farming and cover crops across 286 projects achieved an average yield increase of almost 80 per cent, with benefits for more than 12.6 million people (Pretty et al. 2006, 2011). This is a form of

Table 1 Rapid, Slow and Prolonged Threats at a Basin Scale: White Volta, Mekong and Ganges–Brahmaputra–Meghna

<i>Scale</i>	<i>Rapid onset threat: floods in the White Volta Basin</i>	<i>Slow onset threat: groundwater overdraft and land subsidence in the Mekong Delta, Vietnam</i>	<i>Prolonged threat: climate change in the Ganges–Brahmaputra– Meghna Basin</i>
Household	Destruction of farmlands	Loss of affordable water supply for drinking	Increased risk of damage to rice crops, livestock population, property and human health due to extreme weather events
	Inability to meet food needs	Loss of water to support shrimp and rice production	Increased risk of malnutrition for poor women and children due to intra-household distributional allocation of food resources during scarcity
	Increased farmer migration to urban centres	Increased risk of forced migration due to job loss, water loss, seawater intrusion or coastal flooding	
	Farmer grief and stress	Less resilience to drought and dry season shortages Diminished employment opportunities Impaired household welfare due to health issues	
Community	Reduced agricultural production and income	Increased water treatment costs	Uncertainty in coping and adapting with changes in cropping patterns and crop suitability
	Destruction of houses, roads and bridges	Reduced agricultural production and income	Increase in social destabilisation and enhanced conflict among neighbouring households and communities
	Increased incidence of water-borne diseases	Replacement of drinking water supplies with higher cost alternatives	Increased public health risks from large displaced coastal populations greater variability of water supply
	Accumulation of massive quantities of silt on key community structures Damage and loss of livestock	Less resilience to drought and dry season shortages Reduced economic activities, particularly in non-tradable goods Impaired social welfare due to health issues	Increased risk of river bank erosion and land degradation
National	Decreased agricultural labour availability	Less rice production in key supply region	Changes in magnitude, depth and extent of flood discharge due to geomorphological changes of rivers
	Decreased availability of seeds	Less foreign exchange from shrimp production	Increased risk of dwindling agricultural and livestock production
	Reduced food availability	Higher costs of social welfare support	Increased variability and more intense rainfall events and sediment flows in rivers
	Job losses	Costs of displacing residents from lost coastal areas	Increased soil salinity
Regional		Deepening poverty and food insecurity	Increased frequency of extreme floods and droughts

(Continues)

Table 1 (Continued)

<i>Scale</i>	<i>Rapid onset threat: floods in the White Volta Basin</i>	<i>Slow onset threat: groundwater overdraft and land subsidence in the Mekong Delta, Vietnam</i>	<i>Prolonged threat: climate change in the Ganges–Brahmaputra– Meghna Basin</i>
	Increased transboundary tensions over the management of hydropower dams Exacerbated land degradation	Loss of wetlands and mangrove forests to seawater intrusion and coastal flooding	Upstream snowmelt contributing larger flows to the basin
	Increased food prices		Substantial uncertainty in the timing of monsoon onset Reduction in water-holding capacities and replenishment rates into water bodies, aquifers and ecosystems
	Increased political instability		Changes in geological factors governing aquatic systems
	Destruction of forestry biomass		Decreased resiliency of environmental systems

References: Armah et al. (2010); Brown and Crawford (2008); Erban et al. (2014); Erban et al. (2013); Jeuland et al. (2013); Mirza (2006); Mirza (2011); Mirza and Ahmad (2005); Mirza et al. (2003); Schmidt (2015); Tare et al. (2013); Tschakert et al. (2010); Vaidya and Sharma (2014); Wirsing and Jasparro (2007)

‘scaling up’ of traditional agricultural knowledge (FAO 2011). In other settings, SI solutions have included integrated pest management technology (Khan et al. 2014), systems of rice intensification (SRI-RICE 2015), saline farming (Fedoroff et al. 2010), genetic reengineering (Gready 2014) and aquaponics (Javens 2014).

3.1.2. Limitations

Responses to food security threats primarily focused on production have three drawbacks. First, Tilman et al. (2011) suggest that SI has greater potential in developing contexts, where large differences between current and potential yields can be reduced with minimal environmental externalities. In developed agriculture, there is concern that SI solutions may even promote a ‘production agenda’, using the SI premise as cover to push for further industrial intensification while overlooking the ‘sustainable’ component of the definition (Tomlinson 2013).

Second, Ray et al. (2013) contend that increases in food production alone may not be sufficient to meet projected demand. Others

argue that an SI approach may disregard alternative solutions that explicitly respond to the political economy aspects of food distribution and affordability. In particular, it is estimated that up to one-third of all food produced is not consumed, with wastage occurring in both the consumer and producer supply chains (Lundqvist et al. 2015).

Third, the ramifications of intensification for linked natural systems may be overlooked in SI solutions (Godfray & Garnett 2014). Kuiper and Struik (2014) argue that SI may create a ‘win-win euphoria’ with insufficient attention given to trade-offs and to options outside the direct food production sphere. While intensification may use some unconsumed resources more efficiently on site, through enhanced agronomic practices, eventually, greater levels of production require increased use of energy, water and nutrients, thus creating or exacerbating trade-offs (Chan & Knight 2014). For example, the ‘decoupling’ of water consumption and food productivity in Australia’s Murray–Darling Basin was achieved, in part, by pressurising formerly gravity-fed irrigation systems that dramatically increased energy consumption (Mushtaq et al. 2015). Increased

efficiency of water use in irrigated agriculture can create perverse ‘rebound effects’ wherein overall water use may increase and greater pressure is placed on water resources (Berbel et al. 2015; Ward & Pulido-Velazquez 2008).

3.1.3. Current Thinking

Given that much of the current thinking about SI is focused on production and specific technologies to provide future food security solutions (Fischer et al. 2014; Godfray & Garnett 2014), there is a growing consensus that a broader, more comprehensive transformation in agricultural thinking is critical to achieving desired supply goals (Beddington 2009; Foley et al. 2011). Thus, SI as a response to global food insecurity should be applied as part of a portfolio (Godfray & Garnett 2014) of approaches that includes governance and demand-side solutions, and also smart regulation (Sunstein 2002).

3.2. The Nexus

Speaking on World Water Day in 2011, the Secretary General of the United Nations, Ban-Ki Moon, characterised the challenge of supporting a much larger global population as follows: *As the world charts a more sustainable future, the critical interplay among water, food and energy is one of the most formidable challenges we face.*

This challenge observed by Ban-Ki Moon is exacerbated by increasing competition for land, water and energy that has made trade-offs between natural resources increasingly evident and prompted the search for cross-sector efficiencies and ‘win-win’ solutions. The nexus approach seeks an integrated and coordinated approach to the interdependencies, synergies and trade-offs within the natural resource systems (Stirling 2015) that support food security (FAO 2014). A nexus approach has the advantage of focussing on two or more sectors where tractable actions can be identified and implemented (Hussey et al. 2015b).

The ‘nexus’ considers governance as a key part of the problem, and thus, part of the solution (Lele et al. 2013; Stein et al. 2014) is to

operate at the interface between sectors. The feasible policy set for nexus problems needs to originate from an understanding of the political reasons why rational, available solutions, such as reforming electricity subsidies for irrigation in India, are not already being broadly implemented (Shah et al. 2012). Hence, nexus solutions often include institutional reform guided by stakeholder collaboration (Rodriguez et al. 2013; Stein et al. 2014; UNECE 2014).

3.2.1. Application

The food price hikes of 2007–08 highlighted a need to expand beyond a single-sector focus to multi-sectoral coordination of all the systems that support food security (Grafton et al. 2015a). Beddington’s (2009) ‘perfect storm’ analogy, the concept of sustainable planetary boundaries of Rockström et al. (2009) and the Bonn Declaration (GWSP 2013) all exemplify the need for a major policy shift towards a transdisciplinary approach. Viewing the nexus through a risk lens within the World Economic Forum (Waughray 2011) has generated much interest from the private sector (Lundy & Bowdish 2014) and led, for example, to partnerships between major corporations and non-government organisations around ‘water stewardship’ (WWF 2013).

A transdisciplinary approach towards food, energy, environment and water management is on the agenda of governments, for example, GIZ (2015); international organisations, for example, UN Water (2014) and UNEP (2015); and research consortiums (for example, FE²W Network 2014; the Nexus Network, 2014; Columbia Water Centre, 2015; University of Cambridge, 2015; Water, Land and Ecosystem research program of CGIAR, 2014; and Future Earth, 2015). The FAO, for example, has shifted from its 2011 SI policies to view the nexus as a primary approach to achieving food security (FAO 2014).

The United Nations Economic Commission for Europe has produced a nexus assessment methodology (UNECE 2014) for use under the United Nations Economic Commission for Europe Water Convention that has been trialled in the Alazani/Ganikh Basin (KTH &

UNECE 2014). While differing in emphasis, each nexus framework seeks to understand and assess links between natural resource systems. This is carried out to identify entry points for interventions and then to monitor and evaluate their performance (Bizikova et al. 2013; Hoff 2011; ICIMOD 2015; Rasul 2010).

Approaches that embrace the nexus concept, whether deliberately or not, have sought to decouple, manage and understand resource interconnections to enhance food security. In the Indian state of Gujarat, for example, food, water and energy have been tightly coupled through the use of electricity for groundwater pumping for irrigation. An almost 600 per cent increase in the use of electrical pumps since the 1970s resulted in a crisis of groundwater depletion and salinisation (Shah et al. 2008), and inadequate access to electricity for the industrial sector. An innovative program separated electricity feeder lines for agricultural and non-agricultural uses for effective farm power rationing (rather than charging farmers for electricity) while supplying uninterrupted power supply to non-agricultural users, who pay for the service (IWMI 2011).

3.2.2. *Limitations*

Although it represents a continuation of systems thinking applied in other areas, broad uptake and implementation of the nexus approach in agricultural, environmental and resource management remain elusive in practice (Bizikova et al. 2013; Bradshaw et al. 2014). In part, this is because every case is unique and there are difficulties in devising boundaries and selecting the core systems and connections for a pragmatic assessment (Stein et al. 2014).

When operationalising the nexus, some have presumed that interconnections are understandable and predictable and that mapping connections results in rational policy reform (Bizikova et al. 2013). Neither assumption is necessarily correct. Navigating the political economy of decision-making across food, water, energy and environment sectors is critical but is often neglected (Villamayor-Tomas et al. 2015).

Effective nexus responses require policy and structural reform directed at deploying new

knowledge and technologies, applying cross-sectoral market-mechanisms, and enhancing governance (Hussey et al. 2015a; Pittock et al. 2013). In particular, recognition of spatial and sectoral interdependencies should inform policies, institutions and investments for enhancing water, energy and food security (Conway et al. 2015).

3.2.3. *Current Thinking*

Arguably, actions on the nexus remain largely within the water sector. Broader application of the nexus approach will require greater involvement from the energy and finance sectors (LaBrecque 2014). Greater corporate engagement will also be necessary to generate innovative and tangible solutions (Lundy & Bowdish 2014; Mosello & Moosa 2014). Further, future nexus methodologies will need to adjust to shifting landscapes, such as the increasing penetration of renewable energy technologies, along with the emerging interconnections between unconventional shale gas, groundwater, land and food (Hussey et al. 2015a; LaBrecque 2014). Climate change and the increasing demand for goods and services, due to economic growth, likely will bring greater attention to the interactions involving food, energy and water resources in many countries (Conway et al. 2015).

3.3. *Resilience Thinking*

Folke et al. (2010) define resilience as the capacity of a social–ecological system to continually change and adapt while remaining within critical thresholds (Folke et al. 2010). Others have defined resilience as the capacity of a system to respond to change, especially unexpected and negative shocks, while retaining its ability to deliver a stream of desirable benefits (PMSEIC 2010; Resilience Alliance 2014; Walker & Salt 2006). Both definitions embed the notions of dynamics, response and adaptation. The concept of resilience in food security is most relevant to developing countries, where chronic undernourishment exposes several hundred million people to rapid onset food security threats. Resilience also is applicable in

developed countries where legacies of past resource decisions, ageing infrastructure and environmental degradation intersect with future trends and threats, including climate change, to expose vulnerabilities in previously stable food systems (WWF & SABMiller 2014).

'Resilience thinking' explicitly addresses the challenge of managing food systems under extensive environmental change. It provides a new perspective on planning for threats (Constas et al. 2014) and globally networked risks (Helbing 2013) by reorienting away from the imperative to accurately predict future impacts. Instead, the focus is much more on building robust coping mechanisms (IFPRI 2013; Walker et al. 2009; Wilde 2013) that perform well under a range of future scenarios, and learning from experience as responses are implemented (Curtin & Parker 2014).

Resilience thinking has been proposed as a replacement for the notion of sustainability, given the extensive loss of biodiversity to date, the prospect for further decline in ecosystem integrity and the risks inherent in global climate change (Benson & Craig 2014). Further, emerging global risks, such as the 2008 food price crisis, where simultaneous stresses result in 'system overload' that resulted in multi-systemic crises that cascaded through global networks (Homer-Dixon et al. 2015), highlight the need for much better risk diagnosis and responses.

3.3.1. Application

The resilience perspective will, typically, inform decision-makers seeking to reduce the vulnerability of communities, ecosystems or institutions. It requires identification of the critical variables and actions that maintain the stability of social-ecological systems while not exceeding key thresholds, and supporting the provision of ecosystem goods and services in the presence of systemic threats.

Striving for system resilience involves promoting diversity and flexibility, and building the capacity to adapt and change. Resilience solutions should encompass wider food security issues of availability, affordability, stability and access (Barrett 2010) and require proper

design, monitoring and evaluation that includes measurement of ex ante threats and ex post indicators of change (Béné et al. 2015). Threats may be addressed through interventions in production, consumption, distribution and governance of food systems, as well as climate change mitigation and ecosystem management (Foresight 2011; WLE 2014).

Resilience can be promoted in many ways. To address the food, land and water challenges in the Volta basin, for example, the Water Land and Ecosystems (WLE) initiative worked with communities to plant fruit trees and build resilience through livelihood diversity and ecosystem biodiversity. WLE highlighted opportunities to strengthen governance mechanisms to improve land tenure, using property rights to provide incentives to improve riparian land management and build resilience to sedimentation. Ecosystem restoration and management have also formed a key component of the 'Great Green Wall for the Sahara and Sahel' initiative, which seeks to strengthen resilience of natural and agricultural systems to desertification (FAO 2007, 2013; Sinare & Gordon 2015).

3.3.2. Limitations

Resilience thinking is systems oriented and, hence, is an approach intended to generate solutions that cut across 'silos' (Hoddinott 2014; IFPRI 2013). Nevertheless, a perceived shortcoming of contemporary resilience thinking, in practice, is that it lacks tested approaches to quantify system linkages, uncertainties and possible trade-offs. Béné et al. (2014) suggest also that resilience may not be pro-poor, as interventions intended to increase resilience are not necessarily those that reduce poverty.

Cross-system resilience linkages can be overlooked in practice. For instance, food production resilience may erode the resilience of water systems; national or general resilience may be achieved at the expense of local or specified resilience. Troell et al. (2014) have used aquaculture as an example to highlight this challenge. Growth of the aquaculture sector may achieve enhanced resilience of the

global food system through food diversification and efficient protein generation (Torrissen et al. 2011), but this overlooks the interconnections between aquaculture, fisheries, crops, water, land and energy. Diverting wild feed for aquaculture, for example, can erode food security for low-income groups (Beveridge et al. 2013) if wild fish are depleted and aquatic ecosystems are degraded (Troell et al. 2014).

Aquaculture illustrates why resilience thinking is insightful, but, by adding further complexity to globally interconnected systems (WLE 2014), and without a framework to assist decision-makers, it may fail to generate practical on-the-ground benefits. More importantly, to make a difference to outcomes, resilience thinking must move beyond evaluation to include actions that promote resilience in practice (Grigg et al. 2012).

3.3.3. *Current Thinking*

Over time, the concept of resilience has evolved from ecological to socio-ecological resilience as ecologists have recognised the importance of human-nature interactions and the centrality of human activities to ecological resilience (Kareiva & Marvier 2012). Contemporary approaches have tried to amalgamate resilience thinking with components of the SI or nexus discourses. WLE (2014), for example, has developed a framework that addresses food security, the resilience of ecosystem services and the cross-scale and cross-level interactions (that is, the nexus) that underpin the system. Stringer et al. (2014) have developed an integrated nexus-resilience thinking framework for the purpose of analysing justice and equity in socio-ecological systems. Pretty and Bharucha (2014) have also linked SI with resilience, highlighting vulnerabilities in modern agro-ecosystems, and the importance of strengthening resilience in order to transition towards sustainable agriculture.

4. Responding to and Planning for Risks

A key response to the global challenges of food, energy, environment and water is to link the diagnosis of risks and their potential

consequences to decisions that can control and mitigate those risks. Our examples highlight local complexity and, thus, the need for contextually appropriate solutions. Rather than ‘one-size fits all’ prescriptions, what is needed is a decision-making process that offers principles and methods for addressing risks across food, energy, environment and water. Such a process should be adaptable for application to different spatial and socio-political scales. It must also be sufficiently flexible to incorporate different types of information and knowledge, ‘scale up’ relevant findings in one location to provide insights for decision-making elsewhere, enable both demand-side and supply-side solutions and respond to and plan for the range of rapid, slow and prolonged threats.

The process of identifying and selecting decision options should draw upon and, where relevant, integrate across the three key discourses of SI, the nexus and resilience thinking, among other approaches. SI emphasises resource use and efficient food production. The nexus places understanding of interconnections and governance at the centre of sustainability and focuses on cross-sectoral investments, policies and institutions to drive change. Resilience thinking focuses on system capacity and responses to threats and highlights the need to build resilience in terms of communities, ecosystems and institutions (Table 2).

All three discourses are valuable when determining how to sustainably feed the world in the coming decades—the challenge of global food insecurity—but by themselves, they are insufficient. We contend that these discourses need to align with decision-making processes that explicitly consider systems and the systemic risks that can generate global crises (Homer-Dixon et al. 2015).

4.1. *Risks and Options Assessment for Decision-making*

The ROAD is an adaptive process that assesses risks and possible responses in food, soil, energy and water systems. It is designed to enable decision-makers to make risk-based responses to food, soil, energy and water threats. It is

intended to be a practical means to address threats to food security and offers the prospect of incorporating the insights of SI, the nexus, resilience thinking and other ways of thinking, to generate better, risk-based decisions and outcomes. It is, above all, an action research process that can be applied at different scales to improve decision-making in the presence of systemic risks.

In sum, ROAD is designed to support individuals, households, businesses and governments to assess risks and integrate them into their decisions. Its purpose is to provide a structure for decision-makers to systematically incorporate different classes of scientific information pertaining to natural and social systems.

4.1.1. Definitions

Researchers and practitioners across different disciplines have used a range of definitions for concepts related to risk and uncertainty. We adapt the approach of the International Standards Organisation (2009) for the ROAD process and define the following terms:

- risk: an event with uncertain consequences;
- trigger: an event that is the immediate cause of a risk;
- pre-trigger control: an action that modifies the likelihood or the consequences of a threat and a trigger-causing risk, but before the trigger occurs;
- post-trigger control: an action that modifies the consequences of a threat and a trigger-caused risk, after the trigger occurs;
- mitigant: an action that ameliorates the after-the-event consequences of a risk;
- option: an action that affects risk, that is, a control and/or a mitigant;
- consequence: an event or outcome from realisation of a risk and the application (or lack thereof) of controls and mitigants;
- event: an occurrence or change in a system or state of the world;
- likelihood: an estimate of the chance that an event will occur and can be expressed quantitatively (as a defined probability between 0 and 1), as a probability interval or qualitatively; and

- stakeholder: a person, community or organisation that can affect, be affected by or perceive themselves to be affected by risks and options.

We noted in Section 2 a range of ‘triggers’ in the context of rapid onset, slow onset and prolonged threats. In terms of the ROAD process, triggers comprise a broader set of events that can be more predictable, such as changing seasons, while an ‘option’ is analogous to a ‘risk treatment’.

4.1.2. Components

Figure 1 illustrates the ROAD process, which includes five components: (i) determining the decision space, objectives and stakeholders, or *scope*; (ii) *identifying* the triggers to be assessed; (iii) *assessing* causal risks; (iv) analysing decision *options* involving controls and mitigants, including a summary and justification for the decisions; and (v) *implementing* decisions and reviewing outcomes. ROAD is superficially linear or chronological in the sense that each component of the assessment (with steps within each) builds on previous components. Nevertheless, it may be necessary to revisit and revise previous components, or steps within components, before moving forward. Thus, ROAD is also an iterative and adaptive process. The final and fifth component in the ROAD process provides the foundation for subsequent assessments, and thus, it is also a circular decision-making process.

The ROAD process can be conducted for forward planning to manage potential risks or to respond to risks once they have been triggered. Prior definition of a causal model and possible likelihoods of risks and effectiveness of options provides decision-makers with valuable information to improve risk management. Hence, ROAD is both a strategic and adaptive management tool that can be updated as uncertainties are better understood, causal pathways are better defined through experience and, importantly, as the underlying causal relationships change.

Multiple concepts and approaches are built into the ROAD process. SI is incorporated

Table 2 Perceived Strengths and Limitations of Three Discourses: Sustainable Intensification, the Nexus and Resilience Thinking

<i>Discourse</i>	<i>Summary</i>	<i>Perceived Strengths</i>	<i>Potential limitations</i>
Sustainable intensification	Producing more food from the same or fewer inputs	Defines the end goal rather than prescriptive practices	Insufficient attention to trade-offs, over-focus on supply-side and singular focus on agriculture.
Nexus	Interconnections between food, water, energy and environment	Emphasis on trade-offs, investments, policies and governance; can engage new knowledge, technologies and markets	Difficult to map onto current governance structures and implement in a systematic manner
Resilience thinking	Capacity of a system to respond to threats and retain ability to deliver benefits	Addresses challenge of resource management in presence of uncertainty and threats	Difficult to quantify system linkages, uncertainties and trade-offs

through the identification of baselines and thresholds for food, energy, environment and water systems in Component 1, their comparison against projected consequences in Component 4 and outcomes in Component 5. These baselines and thresholds may be defined in terms of values for key indicators and/or as qualitative statements. The nexus concept is primarily incorporated via the definition of the causal pathways that link events and options across food, energy, environment and water, and also the requirement to consider consequences across these four linked systems. In addition, the governance focus of the nexus is reflected in the definition of the decision-makers, their objectives, and stakeholders and their needs and objectives, as well as in the comparison of consequences and outcomes. Resilience thinking is integrated in ROAD with the focus on linked systems, triggers and the capacity to inform actions that prepare for potential risks. Sustainable development is included through the use of sustainability thresholds and, in particular, the requirement to define and consider the needs of all relevant stakeholders, including the poor and vulnerable.

4.1.3. Application

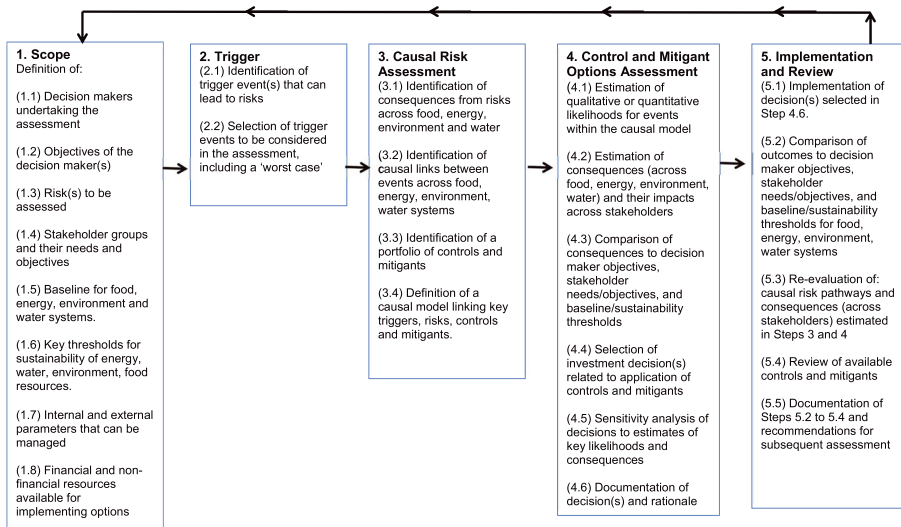
The intended users of ROAD are individuals or groups of decision-makers across different scales. Groups may include individuals with

similar objectives, such as a team within an organisation, or a ROAD process could be conducted as a joint exercise involving participants with different objectives, such as officials from energy and water ministries. The time and effort to apply the ROAD process will depend on the temporal and geographical scale of the decisions at hand, as well as the resources available. For a farmer, it may be a simple, rapid process with a limited information base, but one that would provide a more systematic way to assess and mitigate risks. By contrast, for a state water department responding to food and water risks along a key river system, it would be a much more information-intensive, time-intensive and modelling-intensive process.

A key contribution of ROAD is the causal risk pathways that provide a means to evaluate causes and effects while being explicit about the risks and the outcomes of decisions. Causal risk analysis is not yet mainstream in terms of application but is increasingly being used to undertake risk assessments, to respond to uncertainty and to support better decision-making. Thus far, it has been employed in medical diagnosis, fault diagnosis and safety assessments, among other applications (Fenton & Neil 2012).

The risks and options assessments adopted in Components 3 and 4 define causal pathways and responses whereby there is a trigger that results in a risk that can be influenced by pre-

Figure 1 The Risks and Options Assessment for Decision-making Process



trigger and post-trigger controls. The consequences, after the control, can be influenced by another set of actions or mitigants to ameliorate the after-the-fact consequences. At the start of the causal pathway, the likelihood of the trigger needs to be estimated. This likelihood could be quantitative—in which case, it would be a probability or a probability interval—and based on past data or expert assessment, or based on a qualitative scale of relative likelihood or certainty. The controls at each node along the causal tree also require likelihood of 'effectiveness measures' to ascertain what are the ultimate consequences of the triggers, risks and options employed. The uncertainty inherent in causal models can be accommodated by a sensitivity analysis of options and alternative specifications of likelihoods and consequences in Component 4, as well as the ex post re-evaluation of models in Component 5.

Causal models highlight the options available to manage risks and meet the objectives of decision-makers and stakeholders. Figure 2 presents a simplified illustration of the causal pathways involved in Components 3 and 4 of the ROAD process. This model is a hypothetical representation from the perspective of a farmer in the Murray–Darling Basin in Australia. We assume only one decision-maker and

stakeholder, the farmer, with a single objective: to maximise current and future net income from crop production. Environmental flows in the river provide a range of ecosystem services to the broader community in terms of biodiversity protection and water quality, among other benefits, and also to the farmer in the form of erosion control, recreation, higher property values and long-term productivity of agricultural land (Bonsch et al. 2015). In this causal pathway, there is one primary trigger (drought) and two secondary triggers (reduced river flows and diminished precipitation). The farmer's control in response to the risk is to choose the preferred approaches about how much water should be used in crop production.

For farmers growing water-intensive annual crops, the preferred control may be to sell water and use the revenues generated to help maintain farm income. For a farmer-growing perennials that might degrade or die in the absence of additional water, the preferred strategy might be to purchase water. Buying water may also have additional benefits for river ecosystems due to return flows. On the other hand, a farmer may choose to install a groundwater pump, grow different crops or install drip irrigation.

Each of the farmer's actions has a likelihood of raising or reducing income and maintaining

or degrading river ecosystems. While the control decisions determine the potential consequences against objectives, the farmer may also have mitigant actions available. For instance, if the farmer has a reduced income, he or she has the option to obtain a new, or increase the existing, loan at a bank so as to smooth household consumption.

Our example is highly stylised, and in reality, a much broader range of controls and mitigants would be available to a farmer responding to a larger set of triggers and risks. Moreover, the risks and options would be different from the perspective of a different decision-maker, such as a state government. Nevertheless, it serves to illustrate how cross-system linkages may be incorporated into causal risk analysis and assessment.

Risks and options assessment for decision-making is intended to integrate a range of other complementary decision tools. For example, companion modelling (Barreteau et al. 2012), role-playing games (Ferrand et al. 2013) and other participatory methods could be used across the various components to define the scope, identify events and estimate likelihoods and consequences. In addition, threat and risk assessment and worst-case scenarios (Sunstein 2009) could be integrated into trigger identification. Cost-benefit analysis could be applied when considering consequences and trade-offs and the choice between alternative options to manage risks.

Originally developed in fisheries management, management strategy evaluation (Bunnefeld et al. 2011; Dichmont et al. 2013) could be applied during implementation and review. Further, agent-based models, bio-economic models, and other simulation and optimisation programs could inform the estimation of likelihoods and consequences. None of these tools and methods is, however, necessary to use ROAD. Ultimately, what tools are used to conduct the ROAD process depends on the decision problem at hand and the resources available. We believe that the capacity to integrate multiple sources of information, research methods and types of decision-support tools is a key attribute of ROAD.

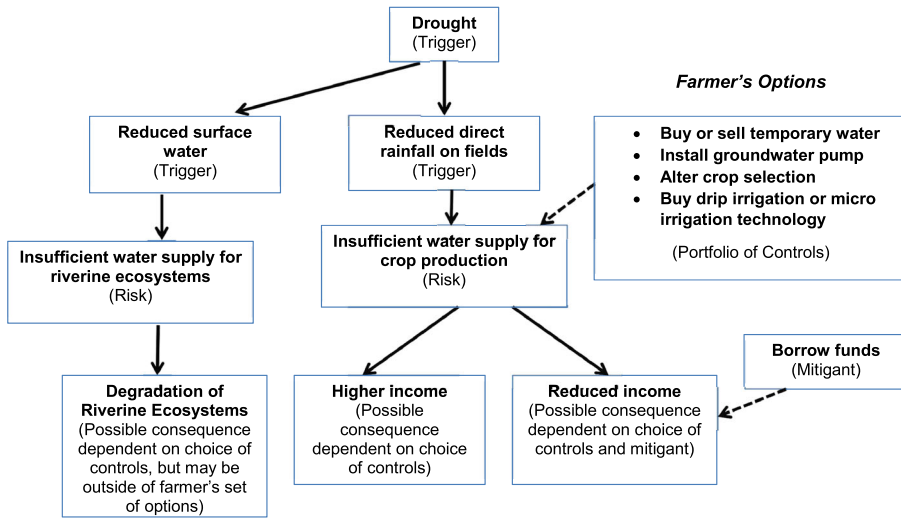
4.1.4. Contribution

The ROAD process is not unique in considering interactions between the food, energy, environment, water sectors and the actions of stakeholders. The drivers, pressures, state, impact and response framework (Kristensesen 2004), water–energy–food framework (Bizikova et al. 2013), ecosystem services and resilience framework (WLE 2014) and multi-scale-integrated analysis of societal and ecosystem metabolism accounting framework (Giampietro et al. 2013), among others, have made important contributions to the analysis of complex decision-making around natural resource security and vulnerability to risks. Others have applied existing conceptual tools to analyse ‘nexus’ problems, such as the institutional analysis and development and value-chain frameworks (Villamayor-Tomas et al. 2015). Quantitative tools have also been developed to assess risks to natural resource security, particularly in the context of water (WBCSD 2015; WRI 2015; WWF & KfW 2015).

We have not yet applied ROAD in a policy setting, and thus, we are not yet able to report how ROAD actually enhances decision-making. Nevertheless, because ROAD focuses on causal risks and the delineation of threats and the actions needed before and after the risks are realised, the approach provides a sound basis for risk-based and evidence-based decisions. As with all decision processes, its practical contribution ultimately depends on how it is applied, and in what circumstances. In our view, the application of ROAD should align with the principles of ‘boundary work’ (Cash et al. 2003; Clark et al. 2011; Kristjansson et al. 2009) to include the following: (i) knowledge user-driven problem definition; (ii) a project-based and solutions-based approach to research objectives; and (iii) a learning orientation that is experimental and embraces successes and failures equally (Kristjansson et al. 2009).

Risks and options assessment for decision-making builds on and synthesises the existing literature and is intended to (i) provide a structured, but flexible process to move from

Figure 2 Hypothetical Causal Pathways for a Murray–Darling Basin Farmer in the Presence of Drought



problem diagnosis to better decision-making that can identify, control and mitigate risks; (ii) identify the key casual pathways between the many complex elements linking food, energy, environment and water systems; and (iii) be flexible for use at different scales, from farmers with limited information and who must make planting decisions for the forthcoming growing season to government departments with teams of modellers engaged in planning across decades. The extent to which ROAD achieves these aspirational goals can only be determined from its application in multiple locations, and for different decision processes.

4.1.5. Implementation

Implementing the ROAD process and applying it in a way that best helps decision-makers require that it be tested and evaluated. Several research questions are pertinent. Under what conditions and circumstances is the ROAD process applicable? For instance, can it be adapted so as to be appropriate for an individual farmer? Or is it better suited for decision-makers with well-trained staff familiar with risk assessment? Further, is the ROAD process applicable in locations where there are limited human and financial capacities? Or is it better suited in places where sophisticated modelling and extensive information resources are

available? Finally, is the ROAD process more amenable to decision-making where the risks are easier to identify and when the trade-offs are clearer? Responses to these questions can only be obtained from testing and applying the ROAD process to assess its weaknesses, identify its strengths and document its contribution to risk-based decision-making.

5. Conclusions

The world is at a crossroads. Past agricultural intensification succeeded at increasing food production faster than the rate of population growth and lifted hundreds of millions of households from poverty and food insecurity. Due largely to inappropriate policies, misguided incentives and poor decision-making, agricultural practices degraded land and water resources and harmed ecosystems.

To feed a global population of more than 9 billion in 2050 and beyond, the world must sustainably intensify its agriculture. More people will live in cities, and many of them will have higher incomes and desire a more diversified diet. Yet many will remain poor, food insecure and live in rural areas. The food, energy and water needs of both rural and urban dwellers must be met in ways that reduce poverty and, critically, sustain the natural resources

and environment on which agriculture depends.

The task ahead is substantial, but not insurmountable. We contend it requires a paradigm shift in how food is produced and resources are used. Continuing to undermine soil fertility and the water quality and quantity needed to supply food is not a long-term option. The food price spikes of 2007–08 and 2010–11, and the global recession of 2008–09, provide a ‘wake-up call’ that systemic global risks can cause cascading failures within and across systems, with rapid speed and devastating consequences.

Key discourses regarding the ‘perfect storm’ recognise the problem and offer solutions, but no single approach is sufficient to achieve a shift towards best practice. We contend that an approach grounded in risk assessment and focused on improving decision-making represents a key step forward. Better, risk-informed decision-making is critically needed to support sustainable increases in food production while explicitly considering the systemic risks across food, energy, environment and water.

The ROAD is a response to this challenge. ROAD is an adaptive and flexible process intended to generate improved responses to risks, and especially systemic risks. It offers the prospect of improved decision-making across institutional scales and locations, and in multiple contexts. The testing and application of ROAD, and in specific landscapes, are required if its potential is to be fully realised. We consider this to be a global priority.

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