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Food security and the environment: Interdisciplinary research to increase productivity while exercising environmental conservation

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A B S T R A C T

Global food insecurity is increasing in absolute terms despite recent decreases in percentage terms. Options to increase food production while protecting the environment exclude further expansion of cropland, leaving increased agricultural productivity as an option assuming we address its associated technological and societal challenges while exercising environmental conservation. Improving productivity requires redoubled efforts in interdisciplinary work to design and implement sound agricultural management practices and efficient use of inputs. Based on a historical perspective of the last few decades on hypothesized environmental limits to food production and looking at prospective futures, we analyze the required type of interdisciplinary research to improve productivity. We conclude that bringing together increased food supply and environmental conservation requires research that integrates engineering, technology, science, policy, and action.

1. Introduction

There are ~800 million undernourished people in the world (~11% of the population), an improvement in the last decade that meets the First Millennium Development Goal of halving the proportion of people who suffer from hunger by 2015 (FAO et al., 2015) (Fig. 1). The world 2015 Global Hunger Index (GHI) improved by 27% relative to 2000 (von Grebmer et al., 2015). This is a consistent trend; according to the United Nations (UN) the proportion of undernourished people decreased from 20% to 16% in the previous decade (UN, 2010).

The Food and Agriculture Organization (FAO) considers four dimensions of food security: food availability, food access, utilization, and stability (FAO, 2006). In this paper, we focus on food availability and in particular food production and its limiting factors related to environmental conditions (e.g., climate, water, soils) and human related factors – such as lack of infrastructure (e.g., irrigation, roads, and food storage), lack of agro-bio-technology (e.g., seeds of water-efficient crops), and inadequate socio-political systems (e.g., fair trade, food justice, governance, and policy).

Several institutions sustain interdisciplinary (ID) research teams to examine impediments to food production; for instance, FAO, the International Food Policy Research Institute (IFPRI), the UN World Food Programme (WFP), the World Bank, the UN Committee on World Food Security (CFS), the International Water Management Institute (IWMI), and the Cereal Systems Initiative for South Asia (CSISA). Global climate change compounds some of these impediments to improve food security and ID approaches to study climate change have become relevant (Ziervogel and Ericksen, 2010).

Societies may not expand cropland without significant environmental risks, leaving increased productivity as the major avenue to increase food production, which demands ID research (IDR) (Acevedo, 2011). In this paper, we provide a historical perspective of the last few decades on environmental limits to food production. While acknowledging the progress made due to the Green Revolution, we look at prospective futures, to realize that the type of IDR required should integrate technology, science, policy, and action. In particular, we advocate more use of the capabilities of qualitative social sciences in order to address the multiplicity of human factors that may impede improvement in food production and more generally in food security.

Our analysis relates to worldwide food production and environmental quality, but we focus on those regions where there is large need to increase the number of people with access to food which in many cases coincide with those regions where food production and environmental quality are in greatest need of reconciliation.

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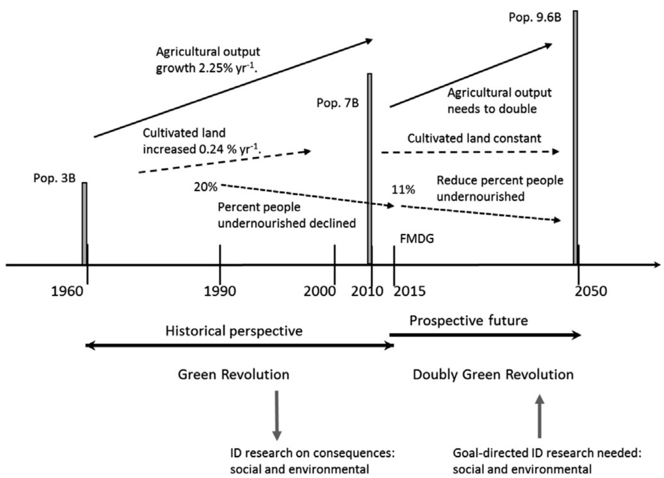

Fig. 1. Historical perspective leading to prospective future. Pop. = Human population. FMDG = First Millennium Development Goal.

2. Historical perspective: the last half of the past century

In the 1960s, the accelerated growth of the world's population led to predictions of increased famines and mortality, and of reaching the limits of growth within a century (Fig. 1) (Meadows et al., 1972). The Malthusian proposition that food demands, growing exponentially with population, would exceed food supplies, growing only arithmetically, seemed inevitable. Yet in the last 50 years, world population has more than doubled while the number of world's starving has not increased, albeit remaining obscenely large.

Our food production per head has generally increased and the prices of food had not shown a substantial tendency to increase but they may start to do so according to recent signals (FAO, 2015). Since 1961, global agricultural output has increased by 2.25% per year, while the increase in land devoted to farming has only increased by 0.24% per year (Fig. 1) (Pardey et al., 2012). Global population increased by 1.7% per year, but the people engaged in farming only grew by 1.2% per year. This apparently good performance has occurred through geographical shifts in global production; most of the increase of the value of food production per head, has happened in the upper middle-income countries (Pardey et al., 2012). For instance, in 1961, Russia accounted for 15% of global wheat production and was the world's largest producer, but by 2008, Russia only accounted for just over 8% of global production, with India and China together accounting for almost 29% (up from 12% in 1961).

The achievements of the last 50 years largely due to the Green Revolution (based on higher-yield varieties of rice, wheat, and maize) have also caused adverse effects on the environment and human health (Kedia and Palis, 2008). Negative effects on agro-ecological functions have in turn resulted in decreased crop yields (Boutsen, 2009). Concerned that the pace of yield improvement had slowed by the turn of the century, Conway (1999) proposes a ‘Doubly Green Revolution’ (Fig. 1) which would be more productive and more ‘green’ (in environmental terms) than the first, and targeted towards the poor.

Indeed, Pardey et al. (2012) provide evidence of the slowdown in world crop yield growth and question whether current trends in agricultural R&D are likely to reverse the decrease in productivity. Global R&D spending has grown impressively in real terms (2005 purchasing power parity, PPP, rates), but this growth has largely happened in the middle-income countries, especially Brazil, India and China. Disappointingly, there is little sign of strong spending growth rates in sub-Saharan Africa, Latin America and the Caribbean, which indicates a growing divide with the poorest countries falling farther behind (Pardey et al., 2012). A major contribution to food production would be to make results from R&D spending in high income and middle-income economies available to the poor farmers in south Asia and Sub-Saharan Africa where R&D is still lagging (Pardey et al., 2016). IDR on effective technology adoption by farmers should accompany the transfer of such R&D output.

3. Prospective futures: the first half of this century

By 2050, human population may grow to 9.6 billion or ~ 2.0 people ha^{-1} of cultivated land (per 2010 land area when we had ~1.5 people ha^{-1}) which calls for sizable increases in agricultural production (Bruinsma, 2009) (Fig. 1). Increasing food production requires expanding cultivated area (extensification) or increasing yields on presently cultivated land (intensification); the latter either by direct increased yields, or through changes to crop mix (fiber, feed, and biofuel). As Hertel (2011) notes, 77% of the growth in global crop production over the last half century resulted from increased yields, 9% from increased cropping intensity, and only 14% from expansion of crop area. Bruinsma (2009) projects that only 9% of future output increases (to 2050) may come from extensification.

Indeed, it is commonly accepted that there is little scope for expansion of agricultural land without encroaching on land devoted to environmental protection. Available land is unevenly distributed between regions and countries, being skewed against those countries that have most need to raise production (Godfray et al., 2010). Irrigated agriculture on prime land has relieved some pressure on land expansion, but many irrigation systems are performing below their potential, calling for improvements in water use efficiency (HLPE, 2015) and the global expansion of irrigated area has stalled to 0.6% per year after growing twice as much in the 1990s.

Yields can be improved with new varieties, produced with sustained R&D, better capable of coping with adverse conditions, but they can also be improved by closing the ‘yield gap’ – the difference between the yield potential of crops in a given agro-ecological and climatic zone and the yields actually achieved by farmers in those zones. Although much of irrigated agriculture around the world, and much of developed country agriculture show rather small yield gaps, the gaps remain very substantial (~50%) in rain-fed agriculture, in much of Africa and of Eastern Europe. If these gaps could be closed, some analysts conclude that we can feed another 2 billion with present technologies, and with present cultivated land areas (Hertel, 2011).

The parts of the world exhibiting substantial yield gaps are also those regions lacking market infrastructure and supply chains. Furthermore, closing these gaps requires more inputs and resources, which will become more constraining in the future. Nevertheless, the emerging price signals should encourage more sustainable adaptations and innovations, providing there is sufficient investment in both agricultural R&D, infrastructure, and institutional reform.

Poverty and lack of access to food are as important as limited food production in determining food insecurity (Scanlan, 2001). Areas with the greatest water loss and land degradation correspond with areas of the highest rural poverty and food insecurity (deVries et al., 2003). Improving food security while limiting impacts on ecosystems calls for both the development of sustainable practices and the appropriate economic and institutional environment (FAO, 2011).

Providing enough, for all, forever, requires more than generating the capacities of supplying food. It also requires adaptation and innovations in what we consume, and in our abilities to generate sustainable incomes to re-create worthwhile livelihoods. Aside from the impressive growth in global food production over the past half century, a major factor in the reduction of relative food insecurity has been the growth in incomes – providing the previously poor with the wherewithal to purchase food. Without growth in incomes, we condemn people to food insecurity, poverty, and ill health. Economic growth is therefore a necessary requirement for both food and livelihood security, and will lead inevitably to both greater demands on our increasingly scarce land resources as well as to substantial changes in diets and associated food requirements.

This dependence on continued economic growth, however, raises a fundamental issue – named by some as the ‘trophic conundrum’ – e.g. Czech (2008), based on ecosystem principles, argues that reconciling the conflict between economic growth and environmental conservation is not feasible. This issue is, essentially, a re-specification of the Malthusian argument in biophysical terms. Viewed as a biological food chain, economies convert primary resources into material consumption goods and services, and there is clearly a limit to this process, implying that continued economic growth can only be associated with continued reduction of environmental quality.

The only apparent reconciliation of this conundrum is innovation – technological change to reduce the impact of our productive activities on our natural environment. The trophic conundrum argument ignores human capacity to generate ‘capital’ as recycled natural resources, in much the same fashion as non-human biophysical forces and activities recycle rocks, and waste, into soils, and water into streams and aquifers. Not only do humans recycle natural resources into man-made resources and assets or ‘capitals’, including social and human capitals, but they also practice both natural and Lamarckian selection in their habits and ‘inherited’ practices – adapting and adjusting their consumption mixes to fit with their opportunities and capabilities. Whether we can produce enough food to feed everyone over the long term, requires more than examination of constraints on natural resources, we must also account for our capacity to adapt and develop technological solutions (Scanlan, 2001).

West et al. (2014) find that there are relatively small sets of options (places, crops, and actions) that could provide enough food to meet the basic needs of continued population growth, while addressing environmental sustainability. They identify “leverage points” that focus on reducing the yield gap, reducing environmental impacts, and delivering more food from what is produced. Closing the yield gap to 50% of attainable yields would contribute calories for ~850 million people; however, regions where closing the gap would be effective are concentrated in Africa, Asia and Eastern Europe. Increased water productivity in precipitation-limited regions has the potential to decrease water consumption by between 8 to 15%. Crops that are used for animal feed and other nonfood uses (e.g., biofuels), diminish the calories available to humans and result in a “diet gap”; if human-edible crops currently used as non-food purposes were re-allocated to feed humans it is estimated that it contribute food for an additional 4 billion people (West et al., 2014). Another opportunity or leverage point identified by West et al. (2014) is to reduce food waste which currently amounts to 30–50% of food production. Small reductions of waste in a few countries could contribute food for several hundred million additional people.

4. IDR on food production and the environment: successes and opportunities

In this section, we provide examples of IDR approaches that have been proposed, debated, and utilized to reconcile food production and the environment. Along with these examples, we identify further ID needs and opportunities. We conclude the section with a discussion of integrative frameworks and identification of funding and publication barriers.

4.1. Agricultural science: natural and social sciences

Today's agricultural disciplines, such as agronomy, crop science, agricultural soil science, and agricultural economics evolved at the frontier between plant biology, soil science, climatology, meteorology, and economics among others (Lélé and Norgaard, 2005). Certainly, the Green Revolution involved the application of various disciplines (e.g., agronomy, hydrology, and farm management), but the revolution itself hardly engaged in truly IDR. Indeed, much of the social science and environmental research stemming from the green revolution is on the consequences of the revolution, rather than undertaken to facilitate and improve it (Fig. 1).

Environment friendly technologies for food production have emerged through IDR between natural and social sciences. These technologies include integrated pest management (IPM), that promotes protecting crops by using natural enemies and thus promoting a healthy environment and people, and natural resource management (NRM) approaches, such as nutrient and pest management (to minimize fertilizer and chemicals) and alternate wetting and drying to save irrigation water (Carrijo et al., 2017).

4.2. Ecological sciences

Ecological disciplines have responded with approaches to research the challenging environmental impacts of food production that constrain production itself. These include soil erosion, global climate change, falling water tables and aquifer depletion (Acevedo, 2011). Reconciliation approaches stemming from ecological perspectives include land-sparing (Green et al., 2005), sustainable intensification (Tilman et al., 2011), agroecological principles and landscape ecology (Perfecto and Vandermeer, 2010; Benoît et al., 2012). Debate is still unfolding on the benefits and potential consequences of these various promising approaches while calls have been made to strengthen this IDR by consideration of social issues including policy and justice (Chappell and LaValle, 2011; Gordon et al., 2016; Hatt et al., 2016).

For this purpose, socio-ecological methods can be useful since they capture interacting socio-economic and natural systems as complex, dynamic, and adaptive. These methodologies include values and attitudes of individuals and policy-making together with natural systems dynamics. Wittman et al. (2016) frame a reconciliation of food security and biodiversity taking into account socio-ecological system properties at multiple scales (from household to global).

4.3. Engineering, technology, quantitative approaches, and modeling

Together with increased collaboration between natural and social sciences, we need to strengthen the collaboration between engineering and the natural sciences, particularly biology. Better yet, we can benefit from increased integrative ID between engineering, natural, and social sciences. The CSISA, with the goal of benefiting > 8 million farmers by the end of 2020, has highlighted the application of engineering in food production systems, particularly in sustainable intensification practices (e.g., Kumar et al., 2018). Examples include development of suitable agricultural machinery, for irrigation, tillage, harvest, and post-harvest; adoption is closely associated with infrastructure including electricity and roads (Biggs and Justice, 2015; Mottaleb et al., 2016). Geospatial technologies (remote sensing and geographic information systems, GIS) play a role in understanding water resources and irrigation (Krupnik et al., 2017). Integrating crop models with GIS allows exploration of water productivity at a variety of spatial scales from the field scale and the whole system or watershed level.

Agricultural engineering departments, which formed by collaboration among several disciplines, have been major contributors of R&D on food production, agricultural extension, and engaged in research of relationships of agriculture and the environment. Moreover, several leading US academic institutions with long standing in agricultural science and engineering have recently developed innovative biological and environmental engineering departments and curricula. This type of initiative enhances collaboration with disciplines closer to biological sciences, such as genomics and industrial biotechnology.

Beyond the traditional engagement of agricultural engineering, which itself formed by ID activities, other engineering disciplines (such as civil, environmental, and electrical) can contribute by collaboration with natural sciences. For instance, ground-based monitoring systems using low cost soil moisture sensors and data collection devices would prove very useful for baseline data and follow up water management interventions (Acevedo, 2011).

Modeling socio-ecological systems allow studying land use dynamics in the context of contemporary hotspots of biodiversity as well as agricultural landscape patterns (Acevedo et al., 2008). Adopting a food systems approach also contributes to models taking into account multiple spatial scales, processes, and levels (Ingram et al., 2010).

From the social sciences, economics and geography have established their role in IDR, contributing quantitative and computational methods such as econometrics, simulation modeling, and geographic information systems. For example, Diagne et al. (2013) used an econometric forecast of impacts of research prioritizing the benefits by discipline (e.g., agronomic, breeding, post-harvest). Quantification and modeling are also part, together with deliberative fora, of an agenda for agricultural and food research based on ID work and a system-wide approach that integrates social and environmental issues (Horton et al., 2017). In particular, working across disciplinary lines can have a transformative effect on each discipline, and allow for integrated thinking to identify, test, and implement technologies and policies (Horton et al., 2017).

Thus, food and environment research requires a holistic or integrated understanding and synthesis of the interrelationships between the people and natural resource base, and this involves socio-cultural, economics, technological, ecological and political dynamics operating at different scales and among different levels of social organizations (Acevedo, 2011; Karunasagar and Karunasagar, 2016).

4.4. Socio-economics

Comparing concepts across disciplines, borrowing successful concepts from one discipline to another, and building analog theories have been traditional approaches to IDR. As an example, consider the analogy between evolution of socio-economic systems and evolution of nature (for which the rules for survival are *exogenous*). In the former, humans make the rules and laws as well as the tools, so our rules for survival are *endogenous* (Harvey, 2008). Conventional economics largely ignores the interactions between politics and economics, and the fundamental differences between ‘capital’ and finance markets. The latter consist of the transfer of ownership of assets and wealth between individuals and organizations (with no obvious natural counterparts), as well as the markets for goods and services (mimicking natural evolution and the survival of the fittest).

The common representation of the three major dimensions of ‘sustainability’ – environmental, economic, and social – takes for granted the political dimension. Moreover, the critical activities of asset development, maintenance, accumulation, and ownership establishment and transfer are also missing. Yet it is precisely these processes and their outcomes – the development and maintenance of our capital stocks, including natural capital in all its multifaceted forms, which underlie any notion of sustainability and which at least partly determine our future capacities and opportunities.

Researchers in the field of ecosystem services often recognize that biology rather than economics should indicate the importance of natural environments to society. Only when our resources become scarce relative to our needs do we take notice and take steps to seek a solution (i.e. ‘put a price’ of the resource). This is a fundamental proposition behind the environmental Kuznets curve (Galeotti et al., 2009), which suggests that economic growth does not necessarily imply continued reduction of environmental quantity and quality. Concerns about conserving the environment typically take second place to growth ambitions during the early stages of economic development, but as wealth and knowledge accumulate, so does concern and action over conservation.

Our institutions (codes and norms of behavior, rules and laws, and socio-economic practices) are fundamental in directing both the types and pace of our technology development. In this sense, meeting the present challenges depends critically on ID that includes social science, to cultivate better futures. We need to take more care over how we do things – the processes, negotiations and transactions through which we reconcile our narrow self-interests (gilt) with our common social interests (guilt) (Harvey, 2008).

4.5. Non-economic social sciences

Anthropology, sociology, and political science are very important especially when considering policy and impacts, but have been underutilized. These disciplines focus on people's culture (beliefs, norms, values, and practices), institutions, social issues, and governance. Their contributions include framing the right questions to define the real problems; developing appropriate interventions that cater to local adaptations; facilitating innovation systems (including knowledge generation, dissemination and utilization); formulation of appropriate policies; and monitoring and evaluation of feedback mechanisms. Most of all, they emphasize engagement and participation, essential if people are to take ownership of their futures.

To illustrate the contributions of non-economic social sciences, consider two experiences at the International Rice Research Institute (IRRI). The first relates to promotion of IPM. In the 1970s, IPM did not gain wide acceptance by farmers when introduced through classroom training, but started to be adopted more broadly in the 1990s when promoted by FAO through the farmer field school, which included farmer participation and experiential learning (Matteson, 2000). The IRRI's anthropologist formed part of an ID team with entomologists and agricultural economists, that helped improve IRRI's IPM interventions for smallholder farmers in Southeast Asia, particularly in the Philippines (Price and Palis, 2016). The anthropologist included farmers’ participation, stimulated scientists to interact with farmers, and developed rice IPM training principles that were later used in the farmer field school. This anthropological approach made a major difference in success of the IPM approaches used now in many Asian countries, and around the world (Braun and Duveskog, 2011).

As a second illustration, consider adoption of NRM technologies in rice production, which had been a challenge because they require adaptation and collective action. IRRI promoted best practices for NRM to help rice farmers achieve increased profitability and food security as well as to achieve environmental sustainability (Rejesus et al., 2014). Anthropological research highlighted the importance of building on farmer knowledge, experiential learning, and social capital to facilitate adoption of NRM technologies and accelerating its spread for small-scale farmers in Asia (Palis et al., 2004).

4.6. Integration frameworks

The goal of IDR is to integrate the epistemological traditions of the individual disciplines in defining the problem and the methodological comparative advantages of the different disciplines in the development of knowledge (Godfray et al., 2010). As Axinn (1997) pointed out, new knowledge tends to be highly specialized and so fragmented that we have been unable to put it together to solve complex problems. Thus, we need to integrate knowledge generated from individual disciplines, and from interactions among disciplines. Clark and Wallace (2015) advance one possible integration framework implemented as a set of operations. These are problem orientation, social process, decision process, multiple methods (mobilized from various disciplines), standpoint (how researchers relate to the problem), and common interests (higher-order goals). Such an integration framework makes explicit the stages of identifying complex issues and the technological solutions to address them. Life cycle thinking and analysis are also seen as a framework to work across disciplines in several science domains such as environmental, technological, social, and economics. This methodology allows identifying problematic issues in food supply chains and prioritizing research goals. It has been demonstrated by application to several case studies (Sala et al., 2017).

Three global change processes (climate, land-use, and economic) compound the challenge of reconciling production and environmental quality (Foley et al., 2011). The impacts of global change on food security are best examined adopting a "food system" view and developing an ID framework to bridge disciplines and to show where each contributes (Ingram et al., 2010). As we implement interventions programs based on IDR, it is important to design standardized outcome measures and share expertise across regions (Gaihre et al., 2016).

Conway (2012) is cautiously optimistic about our ability to increase productivity providing that we make full use of available technologies, increase funding to develop new technologies, employ sustainable practices, and plan strategically at the market, sector and policy levels. An implication of this recipe is that the 'quadruple green' revolution we need (sustainable, effective, equitable and efficient) requires redoubled ID efforts and a combination of innovation, markets, people and political leadership (Fig. 1).

4.7. Funding and publications

ID is formally recognized as an excellent vehicle for innovation and solving complex problems. However, research funding, publications, and academic incentives seem to favor a non-ID behavior; this apparent paradox has been lacking empirical confirmation (Rylance, 2015). For instance, it is often asserted that ID grant proposals are less likely to be funded than disciplinary proposals; Bromham et al. (2016) have recently demonstrated it to hold true using data from one funding agency. The study used an ID distance (IDD) metric that captures the relative representation of different disciplines and their degree of difference and a test case study from almost 20,000 proposals submitted to the Discovery Program of the Australian Research Council over five funding cycles. Reasons for lower probability of success for ID proposals are not clear; some may be due to reviewer's lack of grasp of several disciplines at once, accompanied by a perception of higher-risk and cost (Bromham et al., 2016).

In contrast, other studies have found evidence of ID content in funded projects. For instance, awards from the USA National Science Foundation (NSF) in 2010–2011 were analyzed using a topic model and data mining methods (Nichols, 2014). The ID nature of an award was determined from tags assigned to disciplines and an ID metric based on a diversity distance. In particular, 14,000 awards by the Social, Behavioral, and Economics Sciences (SBE) directorate were found to have a relative high degree of ID, which varies whether the ID includes other disciplines within the directorate or from other directorates.

These studies demonstrate that it is possible to assess the inclusion of ID in funding programs, which would allow funding agencies and donors to guide their efforts to increase funding opportunities for IDR projects.

Publications, another major criterion for tenure and promotion, is a crucial challenge for IDR. The number of ID journals is increasing, but only a few have prestige and high impact factor compared to those of single-discipline journals. Articles in the very prestigious multidisciplinary journals, *Science* and *Nature*, do not include substantially more IDR than other high-ranking disciplinary journals (Solomon et al., 2016). However, the broad reach and high impact of *Science* and *Nature*, has an influence in understanding across disciplines.

Leydesdorff and Rafols (2011) tested metrics to complement journal impact indicator systems with a measure of ID content and impact. These authors used a variety of correlation methods, distance and diversity measures, to rank ID content of ~8000 journals with 12 indicators. This type of methodology could help orient ID researchers in selecting outlets for their work as well as to inform reward systems in academic institutions. However, caution is imperative when considering this quantitative approach. In a review on measuring IDR, Wagner et al. (2011) conclude that beyond the metrics to measure ID output representation in journals, it is important to understand the concept of knowledge integration recognizing that integration can occur within a single mind as well as among a team.

5. Conclusions

The desired IDR to reconcile productivity and conservation should provide an effective way to identify the complex issues requiring solution, to build upon the mobilization of various disciplines, the design of innovative theoretical and methodological frameworks, and the setting up of participatory institutional programs. Providing technological solutions and designing appropriate policy interventions require understanding of the social and environmental processes as a whole. Technological fixes alone would not solve the food security and environment concerns but science, policy, and action could when working all together.

Providing food for all is a primary problem that humanity continues to face. Without food security, societies have a great difficulty to progress in most other aspects of their well-being, particularly a healthy relationship with the environment. It is tempting either to assume that we cannot solve the food production vs. environmental protection dilemma, or to trust that a segment of our modern science will come up with a technological fix. However, we argue that we need a different perspective: that of engaging in goal-directed IDR the full spectrum of science and engineering, from the qualitative to the quantitative, from the experimental to the theoretical. We contend a sustainable doubly green revolution requires this type of research. ID work provides opportunities for synergies between productivity and conservation. To exploit these opportunities, goal-directed IDR is crucial, since researchers, producers, practitioners, and policy makers all need to be involved.

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