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FOOD SECURITY

Global crop improvement networks to bridge technology gaps

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Abstract

To ensure future food security, there is an urgent need for improved co-ordination of agricultural research. While advances in biotechnology hold considerable promise, significant technology gaps exist that may reduce their impact. Examples include an incomplete knowledge of target breeding environments, a limited understanding and/or application of optimal crop management practices, and underfunded extension services. A better co-ordinated and more globalized approach to agricultural research through the implementation of Global Crop Improvement Networks (GCIN) is proposed. Such networks could underpin agricultural research and development by providing the following types of services: (i) increased resolution and precision of environmental information, including meteorological data, soil characteristics, hydrological data, and the identification of environmental 'hotspots' for a range of biotic, abiotic, and socio-economic constraints; (ii) augmented research capacity, including network-based variety and crop management trials, faster and more comprehensive diagnosis of emerging constraints, timely sharing of new technologies, opportunities to focus research efforts better by linking groups with similar productivity constraints and complementary skills, and greater control of experimental variables in field-based phenotyping; and (iii) increased communication and impacts via more effective dissemination of new ideas and products, the integration of information globally to elicit well-timed local responses to productivity threats, an increased profile, and the publicity of threats to food security. Such outputs would help target the translation of research from the laboratory into the field while bringing the constraints of rural communities closer to the scientific community. The GCIN could provide a lens which academia, science councils, and development agencies could use to focus in on themes of common interest, and working platforms to integrate novel research approaches on crop adaptation and rural development.

Key words: Agricultural development, analogue sites, breeding, crop management, extension, food security, networks, partnership, technology gaps.

Introduction

Current trends in population growth suggest that global food production is unlikely to satisfy future demand under predicted climate change scenarios unless the rates of crop improvement are accelerated or radical changes occur in the patterns of human food consumption. The situation is generally more serious in less developed countries (LDCs) where many of the agro-ecosystems are already over-stretched or fragile, investment in agriculture is limited, and climate change is predicted to have its most devastating effects (Jones and Thornton, 2003; Lobell *et al.*, 2008).

Just three staple crops, wheat, maize, and rice, provide approximately 50% of the calories and 42% of the protein for human consumption in LDCs (Braun *et al.*, 2010). Even without climate change, the real cost of wheat, maize, and rice is expected to increase by 60% or more between 2000 and 2050, driven by population and income growth; when climate change is factored in the figures are substantially greater (Nelson *et al.*, 2009). Crop productivity could be further eroded by declining soil quality, water limitations, increasing fertilizer prices, and genetic susceptibility to new pests and diseases (Gregory *et al.*, 2009; Jarvis *et al*, 2010). Rosegrant and Agcaoili (2010) predict that, in the absence of unprecedented, co-ordinated measures to raise productivity, consumers will pay more than double for their staple food by 2050 in real terms. Nelson *et al.* (2009) estimated that, in developing countries, an additional annual investment of US$7.1 billion in agricultural research is needed just to counteract the impact of climate change on child nutrition.

Abbreviations: LDCs, less developed countries; GCIN, Global Crop Improvement Networks; CGIAR, Consultative Group of International Agricultural Research; $G{\times}E$, Genotype by environment; GHG, greenhouse gas; ESSP, Earth System Science Partnership; SMINET, Sorghum Network; ECARSAM, Millet Network; IWIN, International Wheat Improvement Network; IMIN, International Maize Improvement Network; RENACO, West and Central African Cowpea Research Network; IBYAN, International Bean Yield Assessment Network; CIMMYT, International Maize and Wheat Improvement Center; MasAgro, Modernización sustentable de la agricultura tradicional; AGSF, Agricultural Management, Marketing and Finance Service.

There is clearly an urgent need for increased investment in, and the co-ordination of, agricultural research on a regional and global scale (Brown and Funk, 2008). The need to improve the genetic yield potential of crops is widely accepted (Royal Society, 2009; Phillips, 2010). The rates of genetic gains resulting from breeding, however, have decreased in recent decades for most staple crops creating a sense of urgency (Fischer and Edmeades, 2010; Graybosch and Peterson, 2010). Advances in genetic technology hold promise to accelerate the rates of progress; cheap and abundant molecular marker coverage across whole genomes to identify associations with complex traits will increase the precision and efficiency of early generation selection (Bernardo and Yu, 2007). Advances in genome sequencing offer opportunities to identify potentially new sources of allelic variation for the purpose of widening the gene pool available for hybridization (Latha *et al.*, 2004; Kaur *et al.*, 2008). Furthermore, once freedom to operate with transgenic technology becomes more affordable to public as well as private sectors it is almost certain to open opportunities to push back the frontiers of genetic yield potential (Fedoroff *et al.*, 2010), as exemplified by the C_4 rice initiative (Furbank *et al.*, 2009).

However, significant knowledge gaps must be addressed if new genetic technologies are to achieve their full potential. For example, while advances in plant genetics have already delivered complete genetic sequences of several crop species in recent years (Feuillet *et al.*, 2011) our knowledge of the environments to which new genotypes must adapt is still patchy, restricting the impact of new gene deployment. This is a clear example of a technology gap that a more systematic approach to environmental characterization could help bridge.

Although greater access to climatic data, for example, would facilitate crop improvement strategies, weather is a moving target. However, farmers have been using crop management techniques that can buffer crops from the vagaries of the weather for millennia (Thurston, 1992; Fereres and Soriano, 2007). Despite this, our scientific understanding of crop management practices are still limited to a large extent by simple models of nutrient and water supply, while the complex ecology of soil and rhizosphere is not fully understood and even less mined (Morison *et al*, 2008) in spite of recent advances in biotechnology that can be used to dissect the underlying microbiological processes (Berg and Smalla, 2009; Bever *et al.*, 2010). These gaps in knowledge, coupled with restricted information about the nature and environmental characteristics of most cropping systems, especially in developing countries, limit the potential impact of improved cultivars as well as the investments in crop genetics.

Other bottlenecks to increasing the impacts of new genetic technologies include underutilization of genetic resources in research and breeding even among closely related species of cultivated crops (Hajjar and Hodgkin, 2007), a lack of skilled agricultural scientists in the North and South alike (Guimaraes *et al.*, 2006*a*, *b*; Morris *et al.*, 2006); underfunded extension services (Chapman and Tripp, 2003), and a variety of policy issues ranging from intellectual property restrictions (Fedoroff *et al.*, 2010) to a lack of incentives for farmers to adopt new technologies (Denning *et al.*, 2009).

This brief review, rather than addressing the potential of new genetic technologies to enhance crop productivity (Feuillet *et al.*, 2008; Tester and Langridge, 2010) focuses on how Global Crop Improvement Networks (GCIN) can help overcome bottlenecks to their development and application by underpinning a better co-ordinated and more globalized approach to agricultural research and development.

Global Crop Improvement Networks (GCIN)

The economic activity of crop cultivation constitutes a *de facto* global network which, for centuries, has developed and passed on genetic material, learnt and spread new agronomic practices, and tapped a common pool of natural resources and other inputs. A simple conceptual model of crop productivity describes the interaction of genome (G) with environment (E) (i.e. $G{\times}E$) both of which have highly complex dimensions. The complexity of G is becoming ever more evident while E encompasses a range of physical, biotic, and socio-economic factors, all of which interact (Appendix 1a; www.essp.org). For example, the response of crops to unpredictable weather, the constant evolution of pest and diseases, and the depletion of natural resources including water and some key nutrients, represent challenges that are common across the spectrum of crops and have impacted society since agriculture began (Flannery, 1973). As population growth and climate change threaten to reshape society in unpredictable ways, the opportunity to address common agricultural problems systematically rather than through a duplication of effort should be given more serious consideration. The vast number of variable factors and the players involved in this equation make the establishment of global crop improvement networks a useful tool in the quest to attain food security at a global level.

Despite unprecedented impacts, the technologies revolutionizing agriculture during the 20th century have to be refined if crop productivity is to continue to increase. One challenge is to increase genetic diversity in farmers' fields (Smale *et al.*, 2002). It remains difficult to utilize the wealth of genetic diversity coming from breeding programmes for two main reasons: (i) patchy information about the environmental characteristics of target sites; and (ii) a scarcity of trial networks that adequately subsample growing regions. However, by extending the existing breeding-oriented networks formally to encompass a broader range of stakeholders, including agronomists, national extension services, agricultural non-government organizations (NGOs), etc, the impact of both national and international crop improvement programmes would be multiplied. By going one step further and extending the reach to farmers, networks would be linked directly to the production constraints of rural communities.

Global crop improvement networks could be extrapolated from already functioning paradigms. For example, breeders select for disease resistance at so-called 'hotspots' that are especially conducive to their expression (Singh and Trethowan, 2007). This concept can be extended to encompass a fuller range of biotic threats, as well as other environmental and agronomic constraints such as salinity, temporary flooding, frosts, heat shocks, delayed rains, etc, if local information can be incorporated into readily accessible environmental databases. An example of such effort, in relation to production constraints at research stations that test international wheat nurseries, is the Wheat Atlas (CIMMYT, 2010*a*).

The scientific value of GCIN in this context is that it will permit research to be extended from the laboratory into the field by identifying sites which vary for specific limiting factors. It would also facilitate the flow of information from the field back to the laboratory, enabling research to focus on issues most relevant to production sites. For example, by facilitating the identification and use of analogue environments, i.e. sites that are analogous to, but for one reason or another more accessible than, a site of scientific interest such as future climate scenarios (Burke *et al.*, 2009; Verhulst *et al.*, 2011).

Through the formation of impact-driven research hubs, GCIN would provide platforms that facilitate the practical integration of disciplines and technologies by bringing stakeholders together. For example, genome analysis could be more precisely linked to the adaptive responses of crops if target environments are both well defined and accessible for experimentation. On the other hand, the establishment of large-scale long-term crop management platforms at key target sites offering a range of agronomic practices would permit the genetic potential of new crop ideotypes to be tested in a systematic manner.

A value-added aspect of such networks could be the involvement of farmers, especially at remote sites of key interest. Judiciously selected on-farm trials would extend the range of research environments without heavy investment in additional research infrastructure (Govaerts, 2010). The involvement of farmers would also facilitate the dissemination of a larger range of cultivars and/or crop management options. Furthermore, GCIN would provide formal and, potentially, well-funded platforms to support a wide range of extension related activities. The communications dimensions of GCIN would serve to empower a larger range of stakeholders, including seed companies, extension workers, and farmers, by providing more timely feedback on the emerging threats and opportunities in current crop breeding and management paradigms (Appendix 1b; HarvestChoice, 2010).

In summary, given the relatively long lag-time from research to adoption in the agricultural sector, GCIN could serve the role of integrating information globally to elicit well-timed local responses. The networks would facilitate national level breeding, crop management, and socio-economic research platforms, and provide the necessary continuity to develop, as well as link with, international initiatives that address urgent agricultural challenges.

The GCIN concept is not original but rather an extension of already functional networks that have been established by international organizations like the Food and Agriculture Organization of the United Nations (FAO), whose humanitarian goals include 'to defeat hunger, … act as a neutral forum where all nations meet as equals to negotiate, … a source of knowledge and information … with special attention on … the world's poor and hungry people' (e.g. the International Network of Food Data Systems, FAO, 2010). The CGIAR is another example of an organization with similar objectives which has been highly effective in providing global public goods, especially improved technologies including cultivars of staple food crops, which have benefited resource-poor farmers (Lipton and Longhurst, 1989; Evenson and Gollin, 2003). CGIAR centres have already established highly successful research networks in different regions of the world (Braun *et al.*, 2010; CIMMYT, 2010*b*). A good example is the campaign to control the spread of the Ug99 strain of stem rust disease, a disease which, if left unchecked, would eventually lead to a global pandemic in wheat (Singh *et al.*, 2008). This has been made possible through the existence of international disease monitoring networks (Smith *et al.*, 2009). Newer initiatives have started to link decades of field trial data with innovative weather data simulation techniques (Appendix 1c; Lobell *et al.*, 2011). To fit in with these extant efforts and multiply or augment their impact, GCIN would need to embrace the full complexity of the $G{\times}E$ paradigm while being 100% productivity focused.

Crop and land management

Crops and the land they are grown on should be managed effectively so that the full genetic potential of cultivars is realized and the natural resource base is protected. However, while industrial age technologies, including large irrigation schemes, the availability of cheap inorganic N, and increased traction power, have revolutionized the potential to increase crop productivity worldwide, significant yield gaps still exist between achievable and currently realized yields in almost all agro-ecosystems (Lobell *et al.*, 2009; Fischer and Edmeades, 2010). Where these technologies have been applied successfully, yield gaps may be relatively small (e.g. 20–30%) and a variety of potential solutions exist to help close these gaps, assuming that the interventions are economically viable. Good examples include knowledge-based decision-making tools and a new generation of 'precision agriculture' approaches that help farmers plan a cost-effective crop management strategy (Raun *et al.*, 2005; Heng *et al.*, 2007; Ortiz-Monasterio and Raun, 2007; Tilling *et al.*, 2007; Lobell *et al.*, 2009).

Much larger yield gaps exist in regions such as Sub-Saharan Africa where, due to a lack of access to modern technologies, investment could provide significant productivity boosts (Fig. 1). For example, fertilizer rates in Sub-Saharan Africa are about 10% of that in developed economies. However, the key to success in these regions will be to apply technologies in a sustainable way (Twomlow *et al.*, 2011), given that there are a number of major cropping systems worldwide where crop productivity is on the decline due to their inappropriate use (Dawe *et al.*, 2000; Duxbury *et al.*, 2000; Ladha *et al.*, 2003). Excessive

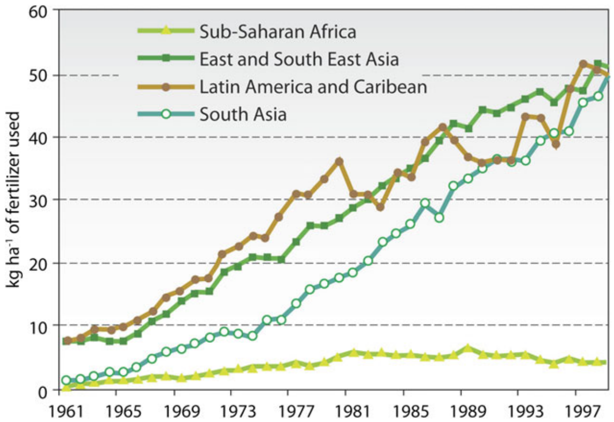

Fig. 1. Change in fertilizer use in the developing world since 1960 (FAO, 2005).

soil cultivation has led to compacted or eroded soils and the use of irrigation water without adequate drainage has led to toxic levels of salinity, resulting in stagnating or declining productivity (Datta and de Jong, 2002). Farmers often respond to this situation by applying more inorganic nutrients which, over the long term, further erode soil organic matter leading to soil degradation. Technological solutions exist to solve these problems, including conservation agriculture approaches to improve soil structure, fertility, and water infiltration (Zhang *et al.*, 2007; Hobbs *et al.*, 2008; Verhulst *et al.*, 2010) and, where salinity is an issue, better drainage (Bhutta and Smedena, 2007). Furthermore, agriculture is the fourth biggest contributor to greenhouse gas (GHG) emissions and research into ways to reduce this through agronomic interventions, while highly promising, is still in its infancy (Ortiz-Monasterio *et al.*, 2010). The establishment of GCIN could underpin both strategic and adaptive crop management research in a number of ways.

(i) Detailed yield-gap mapping would be made possible using environmental information at greater resolution than currently available, including that on weather, soils, cropping systems, and current productivity, and thus providing a basis for future agronomic investment. As an example, microelement deficiency in the soil can vary from site to site depending on the local geology, yet, when correctly diagnosed, can be resolved quite simply with amendments, (Bagci *et al.*, 2007).

(ii) Long-term field-based research platforms supported by GCIN could quantify and conduct research on the cumulative effects of alternative agronomic strategies across a range of agro-ecosystems, providing definitive information on optimal management strategies targeted to specific cropping systems. While such platforms already exist (Abrol *et al.*, 2000; Govaerts, 2010; Verhulst *et al.*, 2011) they are limited in number. This bottleneck highlights a quintessential role of GCIN in extending such platforms to encompass a more representative range of cropping systems through involving larger numbers of stakeholders.

(iii) Crop management platforms for variety testing would permit the systematic evaluation of the adaptation of new cultivars demonstrating their true genetic potential in a defined agro-ecological and systems context. Such a service would allow new crop technologies to be targeted more efficiently, i.e. as a package encompassing genetic and management strategies.

(iv) Productivity trend monitoring would be made possible by GCIN through the ready availability of both long-term crop and weather statistics of sufficient resolution. For example, the pinpointing of stagnant or declining productivity in specific regions could be followed up with surveys to ascertain their causes (which might include a range of factors such as soil degradation, salinization, reduced availability of water, climate change, or socio-economic issues). Timely pinpointing of such problems, accompanied by the prioritization of research to reverse these trends, could avert not only local food security crises, but also reduce the risk of environmental degradation and the loss of agricultural capacity. In this context, the incorporation of crop modelling networks into the GCIN concept would facilitate the prediction of crop productivity under diverse scenarios (Ingram, 1997; Rosenzweig *et al.*, 2011).

(v) Monitoring GHG emissions associated with cropping systems could be achieved systematically through GCIN in ways that identify best and worst practice emissions scenarios. Information could be used to develop incentive schemes to reduce overall GHG emissions (Ortiz-Monasterio *et al.*, 2010).

Globally co-ordinated crop improvement

A publicly funded system of globally co-ordinated crop breeding already exists for a number of crops. The concept was initiated by the late NE Borlaug, father of the Green Revolution, in response to the threat of famines throughout South Asia in the 1960s and was subsequently endorsed by the global development assistance community, giving rise to the CGIAR system (Reynolds and Borlaug, 2006). Although only modestly funded, in his lifetime Borlaug was attributed to having saved more people (from starvation) than any other living person (Bailey, 2000; Paul, 2001), a clear testament to the effectiveness of the well-focused and co-ordinated international collaborative effort that he instigated for wheat improvement (and for which he was awarded the Nobel Peace Prize in 1970). The International Maize and Wheat Improvement Center (CIMMYT), as well as other CGIAR centres, continue to facilitate the delivery of new crop germplasm as global public goods with a principal focus on the needs of LDCs. Impacts are still being realized, for example, in wheat (Ammar *et al.*, 2008; R Singh, personal communication; Y Manes, personal communication), sustained by activities co-ordinated by CIMMYT (Appendix 1d; Braun *et al.*, 2010).

The value of the international wheat breeding effort co-ordinated by CIMMYT is estimated at several billion dollars of extra revenue, annually (Byerlee and Traxler, 1995; Evenson and Rosegrant, 2002; Evenson and Gollin, 2003), spread among millions of farmers (Lipton and Longhurst,

1989) in favourable as well as marginal production environments (Lantican *et al.*, 2003). In addition to providing genetic stocks that are currently represented in about 50% of the wheat areas in LDCs (Lantican *et al.*, 2003; 2005) the international nursery networks have generated unprecedented global databases on the agronomic performance of genetically diverse elite germplasm, based on voluntary contributions from co-operators throughout the North and South, that allow genotypes with specific characteristics to be identified as well as the demarcation of target locations to which breeding and research effort can be focused.

The GCIN concept described previously would extend the reach and effectiveness of such international crop improvement networks, encompassing a broader environmental and disciplinary base. A more comprehensive database for target environments would permit accelerated testing of germplasm and breeding strategies by facilitating the following types of activities.

(i) Monitor genetic gains: e.g. systematic testing of new cultivars across well characterized target agro-ecosystems (Braun *et al.*, 2010).

(ii) Genetic screening: e.g. for resistance to biotic and abiotic stress factors among genetic resources at predefined hot-spots. (Singh and Trethowan, 2007)

(iii) Analogue environment research: e.g. conduct research and breeding pertinent to future climate scenarios (Ingram, 1997; Burke *et al.*, 2009).

(iv) Genetic resource collection: conduct better targeted searches for genetic resources among the wild progenitors of cultivated species using information on specific stress profiles at target search environments (Hodson and White, 2010).

(v) Define target breeding environments: use yield trial data to define/redefine target environments based on genotype by environment interaction (Braun *et al.*, 2010)

(vi) Pinpoint genetic bottlenecks to adaptation: e.g. use information on trait-by-environment interaction to identify specific environmental factors and growth stages that currently represent genetic bottlenecks to yield gains (Reynolds *et al.*, 2004).

(vii) Hypotheses testing: e.g. test the effect of specific adaptive traits and genomic regions across different target environments (Pinto *et al.*, 2010).

Such activities are currently undertaken on a restricted range of target sites, or more often within the experimental conditions that are currently available to researchers. In some cases, especially in the context of more basic crop research, controlled environments are favoured over field conditions. This is understandable, given the unpredictable nature of weather. Nonetheless, where better environmental information can be made available within a reliable field-based research infrastructure, it would not only make it more attractive for researchers to venture outside laboratory-controlled conditions, but also encourage science councils to incorporate the notion that plant research should migrate towards more realistic environments. Through such mechanisms, GCIN would address one of the key challenges identified by Delmer (2005), i.e. plant breeders and laboratory scientists from both the public and private sectors working together to find solutions for the key constraints to crop production.

The GCIN would also provide an invaluable platform for so-called participatory research approaches. The notion of more participatory research in crop adaptation stems precisely from the relatively patchy or imprecise knowledge of many target environments, making it unlikely that centralized variety development and testing approaches can identify optimally adapted cultivars for the full variety of niches within broadly defined agroecosystems. By involving a larger number of environments and researchers in varietal selection, the range of germplasm coming from breeding effort can be more precisely targeted (Scoones and Thompson, 1994; Morris and Bellon, 2004). Comprehensive GCIN would provide platforms for a more systematic approach to working with the many millions of people involved in farming, especially in the developing world.

Extension and training

Tripp's assessment of policies for future rural development (Tripp, 2001) emphasizes that new technologies will be 'information intensive', i.e. they will require increased levels of knowledge. More educated, well-informed farmers are not only better able to recognize and tackle their production constraints but are also more likely to find solution to their site-specific problems (Chapman and Tripp, 2003). Modern extension programmes, therefore, play a key role in information sharing, not only by transferring technology, but through facilitating interactions, building capacity among farmers and encouraging farmers to form their own networks (Navarro, 2006; Govaerts *et al.*, 2009). Essentially, agricultural extension and training can help farmers maximize the potential of their productive assets. However, the need for more responsive extension provision has coincided with deep cuts to publicly-funded extension services in the developing world (Umali-Deininger, 2007).

The breakdown of classical publicly-funded agricultural research and extension services means that these services are now unable to address the needs of farmers, especially those living in marginal environments. Private research and extension provision were expected to replace that previously provided by government (Keynan *et al.*, 1997). This has not been broadly effective (Miehlbradt and McVay, 2003; Chapman and Tripp, 2003). The GCIN infrastructure could play a key role in revitalizing extension services, (i) as a vehicle for the delivery of new technologies, (ii) by providing a multilateral communications platform, and (iii) through direct involvement of farmers and other stakeholders in research networks.

Policy and education

The task of doubling crop yields in the next 40 years is an unprecedented challenge for agricultural scientists, farmers,

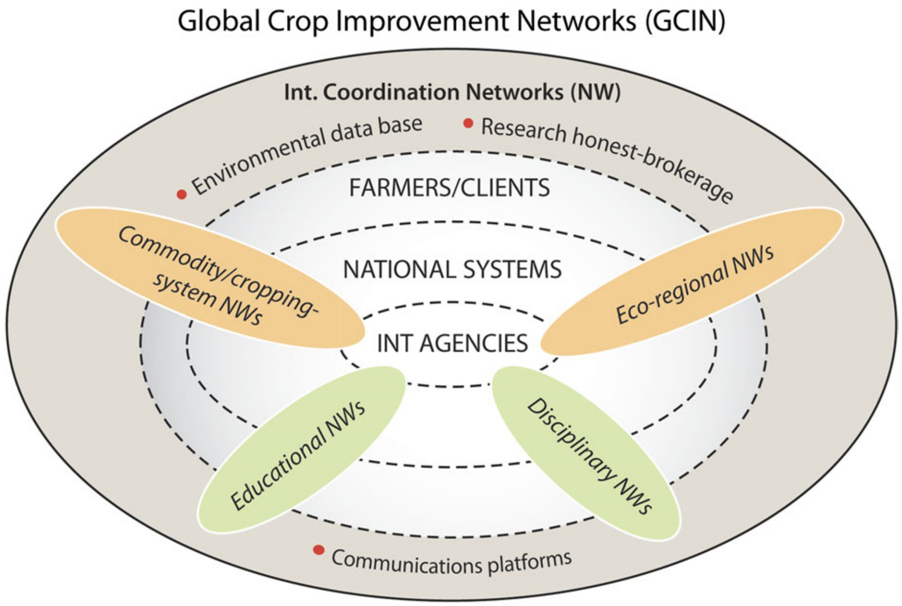

Fig. 2. Theoretical schematic for Global Crop Improvement Networks (GCIN): a series of interlacing networks focused on: commodities or cropping systems, eco-regional issues, educational thrusts, disciplines (e.g. genetics, pathology, agronomy) etc., mutually supported by international co-ordination networks. The latter would include databases for environmental information, research honest-broking facilities to help establish synergistic linkages and priorities at local, regional, and international levels, and communications platforms to promote stakeholder's issues internally and globally. The GCIN would be supported by international agencies (such as FAO, development funding agencies, CGIAR centres, etc); national level systems (including public and private research institutes, extension services, non-government organizations, etc); and would reach out to clients (including farmers, farmer associations, seed industries, members of rural communities, and consumers).

and policy-makers. It is a challenge for humankind and its success or failure will define the environment and the type of society in which we shall live in the future. Agricultural research and development must become a global priority again. The fact that fewer agricultural scientists are trained each year (Guimaraes *et al.*, 2006*a*, *b*; Morris *et al.*, 2006) reflects a surprising complacency about food security. Only policy changes can alter that statistic. Economic growth in LDCs has decreased emphasis on rural issues while, in the West, agriculture has been unfashionable in recent decades. Greater focus of the academic community on food security would help to revive interest in agriculture, while science funding bodies could facilitate the process by encouraging upstream research that addresses fundamental questions associated with sustainable productivity ('Lola' and BREEDWHEAT are examples of recent initiatives in the UK and France, respectively, that attempt to bridge this gap). For example, relatively little has been written about the apparent fundamental genetic limits to yield potential (Zhu *et al.*, 2010; Amthor, 2010) or the true potential of cropping systems to increase productivity (Lobell *et al.*, 2009). A hard body of evidence about the realistic physical limit of crop productivity (not just under favourable conditions but under those where water is limited or unpredictable, or where temperatures or soil chemistry limit biological processes) would make valuable contributions to the scientific literature as well as help establish realistic research goals when estimating potential productivity in future climate scenarios and the true human carrying capacity of the planet. In collaboration with, for example, the Earth System Science Partnership (ESSP) (www.essp.org), GCIN could provide ideal platforms to parameterize, calibrate, and test such models.

Other kinds of policy can help liberalize the biotechnology industry such that technologies which may save lives are shared as widely as possible. Private investment has permitted research at a scale not feasible within the modest budgets of the public domain and has contributed already to food security by increasing yields, especially of maize and soybean, globally. Nonetheless, such impacts are also based on a vast legacy of publicly available technology, information, infrastructure, and genetic resources. The availability of these kinds of public goods could be significantly boosted by GCIN and would hopefully help stimulate further private investment in the food security arena.

Another perplexing issue is the tendency of science councils and international development agencies to duplicate agendas rather than work in tandem. For a research organization, this results in the significantly increased transaction costs associated with compiling a patchwork of grants to address a single comprehensive objective. This is not efficient for either party; further transaction costs involve scientists spending time on work they are not trained to perform while reducing their impact in fields where they have comparative advantage. Giving GCIN a high profile would provide focal points for such agencies

Table 1. Potential outputs of global crop improvement networks (GCIN) to facilitate agricultural research and dissemination of new technologies

Increased resolution and precision of environmental and productivity information
Meteorological data and trends, including climate shifts.
Soil characteristics: physical and chemical properties; indicators of soil quality stability or degradation.
Incidence and evolution of pests, pathogens, and weeds.
Identification of environmental 'hotspots' for a range of biotic and abiotic constraints for use in: (i) germplasm screening, (ii) genetic resource collection, (iii) up-scaling using similarity GIS techniques.
Statistics on prevalent cropping systems, productivity, and crop diversification.
Prediction of crop productivity under diverse scenarios.
Augmented research capacity
GCIN-run variety and crop management trials to permit definition and/or refinement of major target environments for crop improvement and research.
Faster and more comprehensive diagnosis and mapping of emerging constraints (including socio-economic dimensions).
Opportunity to focus research efforts better by linking groups with similar productivity constraints.
Reduce redundancy of efforts through timely sharing of new technologies.
Linking groups with complementary skills via information management and knowledge-sharing platforms.
Increased communication and impacts
Well-informed prioritization of problems and research priorities at both local and regional levels through effective feedback mechanisms among stakeholders.
More systematic targeting and faster dissemination of new agricultural technologies facilitated by comprehensive *ex ante* impacts assessments.
Increased profile for publicizing threats to food security, thereby attracting investment opportunities.
A move away from the 'donor island' funding scenario towards a more concerted and efficient approach facilitated by GCIN platforms.

to link up; permitting a strategic approach to investment whereby a complementary funding mosaic could be developed to address broad themes of common interest.

Structure for GCIN

An effective structure (Fig. 2) should be fashioned based on functionality (Table 1). 'Increased resolution and precision of environmental information' is a key output of GCIN for which the first step would be to identify production zones for which reliable environmental information is available and extrapolate to locations where it is lacking. The 'environmental network' would therefore encompass workers and their organizations with relevant track records in environmental characterization for whom additional resources would permit an extension of their effort. Such an environmental network would cut across all crops and agroecosystems. Logically, it would encompass all willing national programmes, linked by an 'Environmental data co-ordination facility' enabling data to be freely shared and accessed. A regional scale example is presented in Appendix 1e (AfricaTS: http://www.africats.org).

In terms of 'augmenting research capacity' (Table 1), the initial tasks would be to make databases of ongoing crop research themes worldwide with the view of identifying potential synergy and collaborative links. Again, this would rely on the willingness of the national programmes and others to share information. The GCIN would therefore need to develop the roles of 'Research capacity honest-brokers' who, by definition, would be free from conflicts of interest. The resulting databases could be accessed by researchers and funding organizations looking for the means to maximize the benefits and rate of impact of their investments. The information included in the databases would rely on public disclosure in the form of strategy documents, annual and technical reports, and peer-reviewed literature; in other words, information that is generally already publically available, although typically disseminated in a limited fashion. One important role of 'Research capacity honest-brokers' would be to index information to make it readily accessible and sufficiently descriptive so that potential partners can align themselves appropriately. To some extent, these functions are performed by international organizations like the centres of the CGIAR, however, they currently lack the capacity to encompass the full spectrum of cropping systems and stakeholders on which food security depends.

The third main function, 'increased communication', would require dedicated knowledge and technology sharing platforms working in collaboration with the 'Environmental data co-ordination units' and the 'Research capacity honest-brokers' facilitated by sophisticated and user-friendly informatics units. Such platforms would receive and process information and feedback from all network members. An example of this approach that currently focuses at a national level is the recently set up 'Take-it-to-the-Farmer' project in Mexico (Appendix 1f: http://conservacion.cimmyt.org/).

Notwithstanding the GCIN type platforms described (Appendix 1b–f), to take GCIN to the next level, where food security issues can be addressed locally through the integration and application of a global knowledge base, would be a formidable task. New structures would need to work in tandem with extant research organizations worldwide under the supervision of decentralized international governance to ensure efficiency, responsiveness to clients, and that they do not degenerate into being self-serving. As such, GCIN would need to constitute a consortium of interlinking networks each defined by function and economies of scale (Fig. 2). Some are likely to be more efficient if co-ordinated at a more global level, such as 'Environmental data co-ordination'. In other

Table 2. Proposed action steps to initiate GCIN (1–2 year timeframe)

1. Identify sponsor(s) to explore GCIN concept as below.
2.Make tentative list of interested stakeholders (among national agricultural research services, advanced crop research institutes, private breeding companies, international crop improvement organizations, extant international partnerships/networks with food security related activities, development assistance community, government and non-government organizations).
3. Agree on priorities for GCIN (Table 1+) through stakeholder consultation.
4. Make inventory of existing networks (e.g. Appendix 1).
5. Based on (3) and (4) develop a comprehensive strategy that links existing networks while defining main gaps for a functional GCIN.
6. Determine alternative models of effective GCIN structures (e.g. Fig. 1)
7. Make *ex ante* social and economic assessment of added value of GCIN to global agriculture compared with business as usual.
8. Develop an integrated communication and informatics strategy targeted to the different stakeholder groups.
9. Develop a business plan including impact assessment strategies and governance structures.
10. Form a consortium of investors.
11. Develop proposal with representative stakeholders.
12. Initiate GCIN activities as investments become available.

cases, regional, cropping system focused, or disciplinary networks (e.g. Appendix 1) would be more functional as loosely linked autonomous entities with sufficient funding to ensure cohesion. In practice, since the functions of GCIN would naturally evolve over time, it is likely that a flexible needs-driven structure would be most effective.

Conclusions

The technology to overcome the majority of the 'bottlenecks' to productivity discussed in this review already exist. However, given the complicated nature of agriculture, large-scale solutions require careful planning and co-ordination and this is exactly what GCIN could facilitate (Table 1). However, in addition, it would require strong economic and political support to come about (Table 2). In his book, '*Collapse*', the esteemed scientist, Jared Diamond, refers to the isolation of political leaders from the realities that historically have led to ecological and even societal catastrophes (Diamond, 2005). If drastic upheavals of society are to be avoided, due either to widespread food shortage or the overstretching and ultimate decimation of the natural resource base that supports agriculture, political leaders and their administrations must be prepared to delegate responsibility for decision-making to professionals rather than let short-term economic interests, political agendas, and bureaucracy dilute the effectiveness of investments. These professionals should have first-hand experience at improving crop production so that proposed solutions are responsive to the needs of users and efficient in terms of delivery to the ultimate beneficiaries. Ideally, governance of GCIN platforms would constitute individuals with a track record of tangible impacts whose vision is not constrained by disciplinary, commercial, or political bias. Clearly, this is not one group, but a cross-section of agricultural scientists and workers who represent the diverse set of skills and experience needed to make positive changes. A full discussion of how the objectives of GCIN might be achieved is far beyond the scope of this review, however, its effectiveness would ultimately be measured by the food security of those who are, or may become, marginalized in both subsistence as well as agribusiness paradigms.

Appendix 1. Examples of extant networks that represent some of the generic functions of, or potential collaborative linkages with, GCIN type activities.

(a) Earth System Science Partnership (ESSP)

The ESSP is a partnership for the integrated study of the Earth system and the implications for global and regional sustainability. It comprises four international global environmental change research programmes (www.essp.org) whose different objectives include:

(i) Provide the scientific basis for conservation and sustainable use of biodiversity.

(ii) Understand anthropogenic drivers of global environmental change and impacts on human welfare.

(iii) Study the interactions between biological, chemical, and physical processes with human systems in order to respond to global change.

(iv) Draw on climate-related research of more than 185 countries to address aspects of climate change too complex to be addressed unilaterally.

(b) HarvestChoice

An emerging network which generates knowledge products (databases, tools, analyses, findings, and syntheses) designed to improve strategic investment and policy decisions. This framework is being developed and deployed to improve the well-being of poor people in Sub-Saharan Africa and South Asia through more productive and profitable farming. By design, primary knowledge products are currently targeted to the needs of investors, policy-makers, and programme managers, as well as the analysts and technical specialists who support them. Most decisions that HarvestChoice targets are those having implications that cut across country boundaries (HarvestChoice, 2010).

(c) AgSites

In 2009, a group of CGIAR centres (CIAT, CIMMYT, ICRISAT, and IITA) started thinking about past achievements through crop improvement networks in Africa, many of which had stopped working due to a variety of reasons in the past two decades. The idea was to build upon the wealth of information generated by these previous networks and other breeding activities, including hundreds of trial sites managed mainly by National Agricultural Research Systems (NARS) and partly by CGIAR centres in Africa and the related large amounts of variety and breeding line testing data with metadata as well as location-specific climate, soil, and other research data. Crops and the respective testing sites covered in this initiative were initially phaseolus beans, cowpea, soybean, maize, sorghum, and millet and, later, all of CIMMYT's international wheat nursery trial sites in Africa were added. An internet platform (www.africats.org) was created to serve several purposes in order to link interested breeders and related disciplines across institutions, countries, and agro-ecoregions. This platform allows users to find trial sites using dynamic mapping tools while offering them access to a repository of climate and soil information as well as historic trial results. Users can identify homologue sites, i.e. areas with high degrees of similarity compared with their own trial sites or areas of interest for specific breeding efforts in relation to trial sites within the platform. Once having identified a trial site which shows very similar agro-climatic conditions, the user will find contact details for breeders or managers at the site in order to receive appropriate varieties or breeding line or information on technologies that would have a high probability of working in their own agro-climatic zone. A new initiative, started in 2010 as part of the CGIAR research programme on Climate Change and Food Security (CCAFS), expands the original Africa trial sites platform to a global scale (www.agtrials.org) incorporating more crops and more trial sites as well as the associated trial and location data. A new analogue tool will allow the identification of current areas that already show climate change conditions today as predicted for the specific geographic area of interest in the future and thus allow interested researchers to analyse changes in cropping systems and to identify adapted varieties.

(d) The International Wheat Improvement Network (IWIN)

This network, established in the 1950s by NE Borlaug and coordinated by CIMMYT provides approximately 1 000 new genotypes annually to national wheat programmes worldwide as a global public good through the following mechanisms (Reynolds and Borlaug, 2006; Kosina *et al.*, 2007; Braun *et al.*, 2010):

(i) Free exchange of germplasm with all national breeding programmes, public and private worldwide, including accessions from genetic resources collections.

(ii) Centralized breeding hubs that focus on generic needs, i.e. yield potential, yield stability, genetic resistance to a range of biotic and abiotic stresses, consumer-oriented quality traits.

(iii) Distribution of international nurseries specifically targeted to a number of major agro-ecosystems via national wheat programmes worldwide.

(iv) Analysis of international yield trials and free access to all data collected (CIMMYT, 2010a).

(v) Global disease and pest monitoring to ensure the relevance of current local, regional, and global breeding activities (CIMMYT, 2010a).

(vi) Capacity building and training of research partners.

(vii) Regular contact among research partners through consultation, workshops etc. to help identify the latest technology needs.

(e) Africa Trial Sites (www.africats.org)

This is a network for multi-environment cultivar trials in Africa, promoting variety evaluation for crop improvement. Building on the work of research networks such as Sorghum and Millet Networks (SMINET and ECARSAM), International Wheat Improvement Network (IWIN), International maize improvement Network (IMIN), but also vanished RENACO (West and Central African Cowpea Research Network) and IBYAN (International Bean Yield Assessment Network), the site offers environmental data (including homologous models based on climate similarities) and the results of trials.

(f) Take it to the Farmer

An example of a GCIN type approach that currently focuses at a national level is the recently set up 'Take-it-to-the-Farmer' project in Mexico. To help secure Mexico's future food security and bring income opportunities to farmers who have yet to benefit from modern technologies, Mexico and CIMMYT have launched an initiative called Sustainable Modernization of Traditional Agriculture (MasAgro being the Spanish acronym), intended to increase Mexican maize and wheat production by at least 50% over the next 10 years. Through workshops, training, and media strategies (including online interactions and cell phone messaging) it provides location-specific crop management and market information via integrated research and dissemination hubs for maize and wheat production systems in contrasting environments in Mexico, while promoting the appropriate use of integrated soil conservation and water management, more efficient post-harvest technologies, and precision-farming approaches (http://conservacion.cimmyt.org/).

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