Pingali, P. (In Press). The Green Revolution and Crop Diversity (Chapter 12). In D. Hunter, L. Guarino, C. Spillane, and P. McKeown (Eds.) *Handbook of Agricultural Biodiversity*. New York: Routledge.

Chapter 12. The Green Revolution and Crop Biodiversity

Prabhu L. Pingali

Charles H. Dyson School of Applied Economics and Management, Cornell University, Ithaca, New York. *Research support from Megan Witwer and helpful comments from Mathew Abraham are gratefully acknowledged.*

[a]Introduction

The pattern of crop diversity in the fields of the developing world has changed fundamentally over the past 200 years with the intensification and commercialization of agriculture. This process accelerated with the advent of the Green Revolution (GR) in the 1960s when public sector researchers and donors explicitly promoted the international transfer of improved seed varieties to farmers in developing countries. Since the GR, the germplasm that dominates the area planted to the major cereals has shifted from 'landraces' or the locally adapted populations that farmers have historically selected from seed they save, to 'modern varieties' or the more widely adapted seed types produced by scientific plant breeding programs and purchased by farmers.

The yield enhancing seed types enabled the intensification of agriculture in areas of the world with high population densities. Initially they diffused through the environments best suited for their production, spreading later—and unevenly—into less favored areas (Pingali and Smale, 2001). Landraces continue to be grown in the latter and in regions with lower population densities and limited market linkages.

The developing world is at the cusp of a Green Revolution 2.0 (GR 2.0), one that extends the benefits of improved crop technologies into areas that have been by passed by the first Green Revolution and expands the set of improved crops beyond the major three staples – rice, wheat and maize (Pingali, 2012). Sub-Saharan Africa stands out as the region that has benefited the least from GR technologies, despite facing chronic food deficits for decades. The demand for intensification and hence the need for land productivity enhancing seed varieties was low at the start of the GR in the 1960s (Pingali, 2012). Also, in the decades of the 1960s and 1970s, the GR research was not focused on crops important to African smallholders, such as sorghum, millets, cassava and tropical maize (Evenson and Gollin, 2003). In the last decade there has been a significant rise in the introduction and adoption of improved varieties of these crops (Walker and Alwang, 2015). At the same time in Asia, lower potential rice lands, are witnessing the rapid spread of improved drought and flood tolerant varieties (Pandey, 2015).

The advent of GR 2.0 has significant implications for crop biodiversity and genetic diversity. One of the primary outcomes of the original GR was that by intensifying crop production on favorable agricultural lands it allowed significant areas of unfavorable land to be moved out of agriculture. Stenvenson et al. (2013) estimate that the GR saved an estimated 18-27 million hectares from being brought into agricultural production. Would the land sparing benefits hold as the GR 2.0 spreads into more marginal production environments? Also, farming systems in the less favorable environments tend to be very diverse and are home to significant numbers of landraces of traditional food crops, such as millets. Would improved stress tolerant varieties change that system and promote monocultures as has happened in the favorable environments?

This chapter outlines some of the implications of agricultural intensification and the adoption of GR technologies on crop biodiversity and genetic diversity. The first part of the paper describes the drivers of agricultural intensification and its consequences for land use change and crop choice. The second part of the paper describes the spatial and temporal patterns of modern variety diffusion and examines its impact on genetic diversity across modern varieties and within varieties. The final part of the paper presents the prospects for a Green revolution 2.0 with a focus on areas bypassed by the original GR, and discusses its potential consequences for crop biodiversity.

[a]Agricultural intensification, land use change and crop diversity

Intensification of agriculture refers to the increase in output per unit of land used in production, or land productivity. Population densities, expressed as the ratio of labor to land, explain much about where and under which conditions this process has occurred (Boserup, 1981). The transition from low-yield, land-extensive cultivation systems to land-intensive, double- and triple-crop systems is only profitable in societies where the supply of uncultivated land has been exhausted. It is no accident that the modern seed-fertilizer revolution has been most successful in densely populated areas of the world, where traditional mechanisms for enhancing yields per unit area have been exhausted (Hayami and Ruttan, 1985).

Intensive cultivation will also be observed in areas with lower population densities provided that soil conditions are suitable and markets are accessible. Intensification occurs in the less densely populated areas for two reasons: 1) higher prices and elastic demand for output imply that the marginal utility of effort increases, hence farmers in the region will begin cultivating larger areas; and 2) higher returns to labor encourage migration into well-connected areas from neighboring regions with higher transport costs. Examples of regions with low population density but intensive, market-oriented production are the Central Plains of Thailand and parts of South America's Southern Cone.

If the conditions described are not present, labour and other costs associated with intensive agriculture are substantially higher than its incremental economic returns. Intensification of land use and the adoption of yield-enhancing technologies have occurred in traditional as well as modern agricultural systems (Pingali and Smale, 2001).

Agricultural intensification influences the extent of crop diversity in two ways: first through changes in land use patterns; and second, through crop choice changes. Lands that have high agricultural productivity potential, such as the irrigated and high rainfall lowlands, and lands with high soil fertility tend to become the focus of intensification efforts as population densities rise. One also witnesses the concentration of crops that are responsive to intensification pressures, i.e., crops whose productivity can be enhanced through increases in input use. Hence the choice of staple grain crops, such as rice and wheat, over millets and root crops. This change in cropping pattern preceded the

Green Revolution, but the advent of high yielding varieties certainly accelerated the process. Hence the Green Revolution induced ubiquitous monoculture systems in the favorable production environments. The crowding out of traditional millets and pulses from the Indo-Gangetic plains of South Asia, in favor of intensive rice and wheat production is a classic example of such cropping pattern changes (Pingali, 2012).

The lower productive rainfed environments, on the other hand, continue to maintain diversity of crops grown, and for individual staple grain crops, diversity in traditional varieties and land races. Crops grown in the less favorable environments are generally lower yielding and do not respond to higher input use as compared to those grown in the more favorable environments and under higher levels of intensity. These crops, such as traditional millets and sorghum, tend to be better adapted to harsher environmental stresses, such a drought, high temperatures, or flooding, and hence are better suited to the unfavorable environments. Unlike the monoculture systems that are prevalent in the irrigated lands, the stress prone environments tend to have multiple crops on the same field at the same time. The *Milpa* system of Mexico is a great example of inter-cropping of maize, beans and squash in order to ensure farm household food security and diet quality. Furthermore, *milpas* generate public economic value by conserving agrobiodiversity, especially that of maize landraces, which have the potential to contribute unique traits needed by plant breeders for future crop improvement (Birol, et al, 2007).

[a]Spatial and temporal patterns of diffusion on modern varieties[1]

The change in the crop genetic landscape from predominantly traditional to largely modern patterns of genetic variation occurred over the past 200 years and at an accelerated rate since the 1960s with the advent of the Green Revolution (Pingali and Smale, 2001). Evenson and Gollin (2003) show that adoption of modern varieties (for 11 major food crops averaged across all crops) increased rapidly during the two decades of the GR, and even more rapidly in the following decades, from 9% in 1970 to 29% in 1980, 46% in 1990 and 63% by 1998. Moreover, in many areas and in many crops, first-generation modern varieties have been replaced by second- and third-generation modern varieties (Evenson and Gollin, 2003).

Spatial and temporal patterns in the adoption of modern varieties are largely determined by the economic factors affecting their profitability and by the performance of agricultural research institutions and seed industries (Pingali and Smale, 2001). The adoption of these varieties has been most widespread in land-scarce environments with high population densities and/or in areas well-connected to domestic and international markets, where the intensification of agriculture first began. Even in these areas, the profitability of modern variety adoption has been conditioned by the potential productivity of the land under cultivation. For instance, while modern rice and wheat varieties spread rapidly through the irrigated environments, their adoption has been less spectacular in the less favorable environments—the drought-prone and high-temperature environments for wheat, and the drought- and flood-prone environments for rice. For all three cereals, traditional landraces continue to be cultivated in the less favorable production environments across the developing world (Pingali and Heisey, 2001).

Improved varieties for crops such as sorghum, millets, pulses and cassava, were not available until the 1980s (Evenson and Gollin, 2003). Hence the limited expansion of the Green Revolution beyond the favorable irrigated lands. The limited penetration of the Green Revolution into Sub-Saharan Africa up until the 1990s was partly also due to the lack of suitable improved varieties for the traditional staples, especially tropical maize, millets and cassava. The situation has changed dramatically since then. Recent evidence indicates that sub-Saharan Africa is well on its way towards adopting modern varietal technology (Walker and Alwang, 2015).

For instance, the area planted to improved cassava varieties in sub-Saharan Africa doubled from 18% in 1998 to 36% in 2009, and the area under improved maize varieties was at 57% by 2009 in West and Central Africa (Alene et al, 2015). Fuglie and Marder (2015) report that the area under improved varieties doubled from 20 to 40 million hectares between 2000 and 2010. '*This was achieved by deepening the pool of improved varieties available to farmers, both in terms of their adaptability to more environments but especially to a wider set of crops beyond the major cereal grains, including oilseeds, legumes, roots, tubers and bananas'* (Fuglie and Marder, 2015, p356). But, Sub-Saharan Africa still has improved variety diffusion rates that are significantly below those of rainfed areas in other parts of the World. The converse to this statement is of course, that sub-Saharan Africa is still home to significant diversity in traditional varieties and land races of food crops.

In the case of rainfed environments in South Asia, Pandey et al., (2015) indicate that the adoption of modern rice varieties, specifically targeted for those environments, increased substantially since 1998. By 2010 modern varieties occupied over 80% of the rainfed lowland rice growing area in the region, an average annual increase in adoption level in the range of 1-3% between 1998 and 2010. The rapid spread of improved varieties in the stress prone environments raises concerns about the crowding out of crop diversity in favor of staple grain monoculture systems. A potential repeat of the Green Revolution experience witnessed in the irrigated lowlands of Asia.

[b]Narrowing of crop genetic diversity?

Crop genetic diversity broadly defined refers to the genetic variation embodied in seed and expressed when challenged by natural and human selection pressure. In applied genetics, diversity refers to the variance among alternative forms of a gene (alleles) at individual gene positions on a chromosome (loci), among several loci, among individual plants in a population, or among populations (Brown et al, 1990). Diversity can be measured by accessions of seed held in gene banks, lines or populations utilized in crop-breeding programs, or varieties cultivated by farmers (cultivars). However, crop genetic diversity cannot be literally or entirely observed at any point in time; it can only be indicated with reference to a specific crop population and analytical perspective (Smale, 1997).

Whether the changes in crop varietal adoption induced by the Green Revolution have resulted in a narrowing of genetic diversity is an issue that remains largely unresolved due to conceptual and practical difficulties. Scientists disagree about what constitutes genetic narrowing or when such narrowing may have occurred. Several dimensions of diversity must be considered in this regard, including both the spatial and temporal variation between landraces and modern elite cultivars and the variation within modern cultivars (Fu, 2015).

According to Smale (1997), the adoption of modern varieties has been characterized first by a concentration on a few varieties followed by an expansion in their numbers as more varieties became available. Porceddu et al. (1988) described two major stages of genetic narrowing in wheat during modern times. The first occurred in the 19th century when scientific plant breeding responded to the demand for new plant types. Farming systems emerged that were based on the intensive use of land and labor, livestock production, and the use of organic manure. Changes in cultivation methods favored genotypes that diverted large amounts of photosynthates into the ear and grain. Bell (1987) reports that the engineering innovations of the late 19th century led to the establishment of extensive wheat-growing areas in North America, Australia and parts of South America. In other words, mechanization of agriculture dictated uniformity in plant type.

According to Porceddu et al. (1988), a second stage of narrowing occurred in the 20th century, when genes were introduced to produce major changes in plant type. Use of the dwarfing genes Rht1 and Rht2, for example, conferred a positive genotype-by-environment interaction in which yield increases proved greater given a certain combination of soil moisture, soil fertility, and weed control. Varieties carrying these dwarfing genes were developed by Norman Borlaug with the national breeding program in Mexico and later by the CIMMYT. They became known as the Green Revolution wheat or modern wheat varieties.

As the process of modernization proceeded and the offerings of scientific breeding programs expanded, the pattern of concentration declined in many European and North American countries (Lupton, 1992; Dalrymple, 1988, cited in Smale, 1997). Similarly in the early years of the GR, the dominant cultivar occupied over 80% of the wheat area in the Indian Punjab, but this share fell below 50% by 1985. By 1990, the top five bread wheat cultivars covered approximately 36% of the global wheat area planted to modern varieties (Smale, 1997).

Comparing counts of landraces and modern varieties over time may not provide a meaningful index of genetic narrowing. They also imply that even if reliable samples of the landraces originally cultivated in an area could be obtained, analyses comparing their genetic diversity might provide only part of the answer regarding genetic narrowing. While the landrace in the farmers' field is a heterogeneous population of plants, it is derived from generations of selection by local farmers and is therefore likely to be local in adaptation (Pingali and Smale, 2001).

Evenson and Gollin's (1997) summary of the history of rice breeding suggests a process of continual expansion and narrowing of the genetic pool. Organized breeding efforts probably date earlier than A.D. 1000 in China. Modern efforts can be traced to the late 19th century in several parts of Asia. In temperate East Asia, the first significant advance were made by Japanese farmers and scientists when they developed relatively short-statured and fertilizer-responsive cultivars. Known as the *rono* varieties, these belonged to the *japonica* class of rice and were widely cultivated in Japan as early as the 1890s. During the Japanese occupation of Taiwan in the early part of the 20th century, Japanese scientists sought to adapt these varieties to the more tropical conditions of Taiwan. At the same time, researchers in tropical Asia were seeking more productive varieties of rice from the *indica* and *javanica* classes of rice. After World War II, the Food and Agriculture Organization of the United Nations (FAO) initiated a program to cross *indica* rice with *japonicas* as a means of increasing rice yields, culminating in the formation of IRRI and the GR varieties of rice.

To Vaughan and Chang (1992), genetic narrowing in modern rice began early in the 20th century. Development projects, population increases, and forest clearing in Asia were the primary causes of the loss of wild and cultivated rice landraces. In the Mekong Delta, the replacement of traditional deep water rice by irrigated rice occurred with drainage and irrigation schemes that were introduced during the French colonial period. On the other hand, Ford-Lloyd et al. (2008) argue, based on their analysis of data of 33 years of rice land race collections from 1962 to 1995, that they have not detected any significant reduction of actual genetic diversity of traditional rice land races in use by farmers. They assert that it is possible to conclude that genetic diversity in rice maintained *in situ* has continued to survive throughout South and Southeast Asia through their study period. Part of the reason for high prevalence of land races is that modern variety use is very limited in the low productive rice lands, such as drought prone and flood prone environments, in these areas traditional rice varieties continue to be used.

Goodman (1995) reports that the major portion of the variability now found in maize developed before European contact (c. 1500), and several of the most widely grown races, including the commercially important Corn Belt dents, developed later. During the ‘corn show era' in the 19th century US, farmers exhibited their open-pollinated varieties locally and emphasis was placed on uniformity and conformity to an 'ideal type'. By the early 1950s, essentially all of the maize grown in the Corn Belt was double-cross hybrid. After the late 1950s, more and more farmers in the US Corn Belt grew single-cross rather than double-cross hybrids. Because single-cross seed must be produced on an inbred line, this type of selection contributed to a marked loss of variability in US breeding materials. To Goodman, a countervailing influence during the past 25 years has been the emphasis by public researchers on development of improved maize populations.

Not all scientists agree about what constitutes genetic narrowing or precisely when such narrowing has occurred. For instance, in contradiction with Porceddu et al. (1988), Hawkes (1983) cites the introduction of Rht1 and Rht2 genes into western wheat breeding lines as an example of how diversity has been broadened by scientific plant breeders. The Japanese line Norin 10 carried the dwarfing genes from the landrace Daruma, believed to be of Korean origin. Similarly, the efforts to increase rice yields by crossing *japonica* and *indica* classes of rice extended the gene pool accessible to rice breeders. As these examples suggest, in modern agriculture, today's broadening of the genetic pool in a plant breeding program may lead to a narrowing of the breadth of materials grown by farmers precisely because such innovations often produce varieties that are popular.

[b]Genetic diversity within modern varieties

Part of the concern for genetic narrowing is based on the perception that, with time, conventional plant breeding practices inevitably restrict the genetic base of modern varieties. The evidence from studies on the parentage of modern varieties of the major staples lends little support to this view (Witcombe, 1999). In an analysis of genealogies of 1,709 modern rice varieties, Evenson and Gollin (1998) found that while a variety released in the 1960s had three landraces in its pedigree, more recent releases have 25 or more. The complexity of rice pedigrees, in terms of parental combinations, geographical origin and number of ancestors, has expanded over time. A similar pattern has been shown for about 800 wheat varieties released in the developing world since the 1960s (Smale, 1997). The average number of distinct landraces found in bread wheat pedigrees grew from around 20 in the mid-1960s to about 50 in 1990.

Skovmand and de Lacy (1999) analyzed the distance among coefficients of parentage for a historical set of CIMMYT wheat varieties over the past four decades. Their results show a rate of increase in genealogical diversity that is positive, but decreases over time, with marked expansion in genealogies from 1950 to 1967 and gradual flattening through the 1990s. If progenitors were recycled and reused, the distance among them would decrease over time and the slope of the line would be negative. Kazi et al. (2013) provide evidence that bringing genes from wild relatives of wheat into breeding populations more recently has enhanced the gene pool and its utilization for managing various biotic and abiotic stresses.

Smale (2000) further points out that evidence from a number of studies does not support the pessimistic view that genetic base of modern wheat varieties is restricted and tends to decline with the introduction of modern varieties. She argues that genealogical analyses show a significant positive trend in the number of distinct land race ancestors in the pedigrees of over a thousand varieties of spring bread wheat released in the developing world since the start of the Green Revolution in 1966.

Less evidence is available worldwide on trends in the pedigrees or ancestry of maize varieties than for rice and wheat, in part because that information is confidential in an increasingly privatized industry. Following the epidemic of corn blight in the US crop in 1970, the National Research Council (1972) concluded that the genetic base of maize in the US was sufficiently narrow to justify concern. Duvick (1984) found that during the ten years following the 1970 epidemic, breeders had broadened their germplasm pools.

Molecular markers, like genealogies, can be used to construct indicators of the latent diversity in a set of crop populations. Using molecular markers, Donini et al. (2005), compared changes in genetic diversity between 'old' (1930s) versus 'modern' (1990s) UK bread wheat varieties and concluded that there is no objective evidence to support the assertion that modern plant breeding has reduced the genetic diversity of UK wheat. Molecular evidence for a set of CIMMYT wheat varieties indicates that genetic distance has been maintained among major parents and popular varieties over the past 30 years. Since many of the varieties of spring bread wheat grown in the developing world have a combination of CIMMYT and locally-bred materials in their ancestry (Heisey et al, 1999), these data represent a lower bound on actual genetic diversity. Furthermore, the genetic diversity that is accessible to conventional plant breeders today includes not only spring bread wheat, of course, but also wheat types with different growing habit, close relatives and wild grasses (Smith, et al, 2015). Techniques of biotechnology may traverse the species barriers faced by conventional breeders (Moreta et al, 2015).

[a]Green Revolution 2.0 and crop biodiversity

GR 2.0 is already beginning to take place, and it is happening in low-income countries as well as in emerging economies (Pingali, 2012). Low-income countries, many of them in sub-Saharan Africa, that have been bypassed by the Green revolution, still face chronic hunger and poverty. They continue to be plagued by the age-old constraints to enhancing productivity growth, such as the lack of technology, poor market infrastructure, appropriate institutions and an enabling policy environment (Binswanger and McCalla, 2010). Emerging economies, including much of Asia where gains from the first GR were concentrated, are well on their way towards agricultural modernization and structural transformation (Timmer, 2007). The challenge for agriculture in the emerging economies, is to integrate smallholders into value chains, maintain their competitiveness, and close the inter-regional income gap (Pingali, 2010).

Pingali (2012) argues that a confluence of factors has come together in recent years to generate renewed interest in agriculture and spur the early stages of GR 2.0. In the low-income countries, continued levels of food deficits and the reliance on food aid and food imports, have reintroduced agriculture as an engine of growth on the policy agenda. African leaders have acknowledged the critical role of agriculture in their development process and that lack of investment in the sector would only leave them further behind. The CAADP declaration of 2006 and resulting pledges by African Heads of State to increase agricultural investments demonstrated their commitment to improve the agriculture sector. (The Comprehensive Africa Agriculture Development Programme (CAADP) is the agricultural program of the New Partnership for Africa's Development (NEPAD), an initiative of the African Union). There is also an increasing awareness of the detrimental impacts of climate change on food security, especially for tropical agriculture systems in low-income countries (Byerlee et al, 2009).

In the emerging economies, growing private sector interest in investing in the agricultural sector has created an agricultural renaissance (Pingali, 2010). Supermarkets are spreading rapidly across urban areas in emerging economies and are encouraging national and multi-national agri-business investments along the fresh produce value chains in these countries (Reardon and Minten, 2011). Consequently staple crop monoculture systems popularized by the Green Revolution are diversifying into high value horticulture and livestock production. Despite these positive developments, inter-regional differences in productivity and poverty persist in many emerging economies. Rising demand for feed and biofuels, as well as technological advances in breeding for stress tolerance could result in a revitalization of the marginal areas. The rapid rise of hybrid maize production in Eastern India is a case in point (Gulati and Dixon, 2008). Finally, at the global level, the food price crisis of 2008, sustained high prices, and more recent peaks observed in 2011 and 2012 have brought agriculture back onto the global and national agendas (FAO, 2011).

[b]What are the implications for crop biodiversity?

As the Green Revolution 2.0 spreads to regions that have been by passed by the original Green Revolution, familiar concerns about the consequence for sustaining crop biodiversity will emerge. In order to meet the unabated rise in demand for food due to a growing population and rising incomes, the GR 2.0 would need to enhance productivity both on the favorable lands as well as the more marginal production environments. Continued focus on yield enhancing technical change is the primary mechanism for ensuring that lands will continue to be spared for non-agricultural uses, including for biodiversity conservation. Balmford et al. (2005) state that '*Conservationists should be as concerned about future agricultural yields as they are about population growth and rising per capita consumption'*. Agricultural R&D can help in the quest for sustainable biodiversity conservation.

Rising incomes and the consequent decline in per capita consumption of staple cereals, such as rice and wheat, provide an opportunity for moving away from monoculture systems and towards more diversified cropping systems (Pingali, 2015). This would be particularly true in the favorable production environments given their better market connectivity and irrigation and power infrastructure. However, we may see the reverse for the less favorable environments, the movement towards monoculture systems, with the advent of improved stress tolerant varieties, especially when there are only a few successful ones. Pandey et al. (2015) point to the spread of 'mega' varieties, in other words single varieties of rice that cover large areas in South Asia. One such variety, 'Swarna', has spread widely throughout the rainfed rice lands in India, to the extent of 30% acreage in some Eastern Indian states. The successful spread of a few rainfed varieties extend the concern about the narrowing of crop genetic diversity from the favorable environments to the unfavorable ones.

What about genetic diversity within varieties, will it rise or fall? The integration of cereal land races into modern breeding programs could alleviate some of the risk of loss in genetic diversity within improved varieties (Smith et al, 2015). It could also lead to the incorporation of positive traits into new varieties or breeding populations for more sustainable agricultural production. In particular their potential as sources of novel genes for disease and abiotic stress resistance, or for enhancing nutrient use efficiency and improving the nutrition quality of staple grains (Newton et al, 2010). Continued genetic improvement does not necessarily lead to loss of genetic diversity in areas where modern varieties dominate—especially when access to germplasm is relatively unrestricted and innovative plant breeding strategies may be employed. Access to diverse sources of germplasm, including land races and wild relatives, is therefore of great importance to the success of public and private breeding programs and the supply of varieties in modern agriculture (Pingali and Smale, 2001).

What, then, is the future of land races/traditional varieties? The coexistence of varieties and landraces of particularly crops may persist where market-based incentives exist. For example, in Asia, traditional varieties are generally of higher quality and fetch premium prices in the market. Thailand still grows low-yielding traditional rainfed varieties extensively for the export market. Basmati rice production has expanded significantly in India and Pakistan, both for domestic as well as export markets. Traditional japonica rices have risen in popularity across East Asia and are sold at a substantial premium. Quinoa a crop native to the Andean Mountains has become very popular in the developed world due to its nutritional qualities. Once a neglected crop, it is now receiving a lot of attention from Andean farmers as an income growth opportunity (Massawe et al, 2016). Teff from Ethiopia has been making recent inroads into developed country diets. See Massawe et al. (2016) for a review of under-utilized crops that have become or could become attractive to western consumers due to their nutritive qualities. Market based incentives could play a major role in reviving the prospects for under-utilized crops and ensuring their *in situ* conservation.

[a]Conclusions

Agricultural intensification, and the adoption of modern varieties of the major staple crops led to the ubiquitous monoculture systems in the favorable production environments across the developing world. The lower productive rainfed environments, on the other hand, continue to maintain diversity of crops grown, such as traditional millets and root crops. These environments have also sustained the cultivation of landraces of rice, wheat and maize. Narrowing of crop genetic diversity in the GR areas has been averted to some extent by the replacement of the first generation modern varieties with second and third generation varieties in more recent decades. The expansion in the numbers of varieties available through crop breeding programs has reduced the risk that intensive production systems would concentrate on a few dominant varieties. Modern plant breeding has also helped expand the genetic base of modern varieties by incorporating genes from landraces and wild relatives of staple grains into the breeding populations.

This chapter argues that areas that have been bypassed by the original GR are now witnessing intensification and agricultural productivity growth. This GR 2.0 is being observed in parts of sub-Saharan Africa as well as in the unfavorable environments of South Asia. Improved varieties of sorghum, millet, cassava and tropical maize, are being increasingly adopted by African smallholders. In South Asia, rice varieties that are tolerant to drought, and to flooding, have made major inroads into the stress prone environments that were bypassed by the original GR.

While the food security benefits of the GR 2.0 are obvious, there are significant concerns about the consequences for crop biodiversity. The spread of improved varieties of the traditional African crops could lead to the encroachment of monoculture systems in areas where multi crop farming systems sustain diversity and landraces. In South Asia, the spread of small numbers of ‘mega’ varieties of rice that are stress tolerant could lead to the risk of genetic narrowing in rainfed environments where multiple landraces are cultivated today. As GR 2.0 proceeds it would be important to learn from original GR in terms of the appropriate mechanisms to balance food security and crop biodiversity concerns.

[a]Footnotes

[1] This section builds on material presented in Pingali and Smale (2001).

References

Alene, A. D., Abdoulaye, T., Rusike, J., Manyong, V. and Walker, T. S. (2015) ‘The effectiveness of crop improvement programmes from the perspectives of varietal output and adoption: cassava, cowpea, soybean and yam in sub-Saharan Africa and maize in West and Central Africa', in T. S. Walker and J. Alwang (eds) *Crop Improvement, Adoption, and Impact of improved varieties in Food Crops in Sub-Saharan Africa*, CAB International, Wallingford, UK

Balmford, A., Green, R. E. and Scharlemann, J. P. W. (2005) 'Sparing land for nature: exploring the potential impact of changes in agricultural yield on the area needed for crop production', *Global Change Biology*, vol 11, pp1594–1605

Bell, G. D. H. (1987) 'The history of wheat cultivation' in F. G. H. Lupton (ed) *Wheat Breeding: Its Scientific Basis*, Chapman & Hall, London, UK

Binswanger-Mkhize, H. and McCalla., A. F. (2010) 'The changing context and prospects for agricultural and rural development in Africa', pp3571–3712 in P. L. Pingali and R. E. Evenson (eds) *Handbook of Agricultural Economics Vol. 4* (4th ed), Elsevier B.V., Oxford. UK

Boserup, E. (1981) *Population and Technological Change: A Study of Long term Change*, Chicago University Press, Chicago, IL, USA

Brown, A. H., Clegg, M. T., Kahler, A. L. and Weir, B. S. (eds) (1990) *Plant Population Genetics, Breeding and Genetic Resources*, Sinauer Associates, Sunderland, MA, USA

Brussaard, L., Caron, P., Campbell, B., Lipper, L., Mainka, S., Rabbinge, R., Babin, D. and Pulleman, M. (2010) 'Reconciling biodiversity conservation and food security: scientific challenges for a new agriculture', *Current Opinion in Environmental Sustainability*, vol 2, pp34–42

Byerlee, D., de Janvry, A. and Sadoulet, E. (2009) 'Agriculture for development: toward a new paradigm', *Annual Review of Resource Economics*, vol 1, pp15–31

Dalrymple, D. (1988) 'Changes in wheat varieties and yields in the United States, 1919-1984', *Agricultural History*, vol 62, pp20–36

Donini, P., Law, J., Koebner, R., Reeves, J. and Cooke, R. (2005) 'The impact of breeding on genetic diversity and erosion in bread wheat', *Plant Genetic Resources: Characteristics and Utilization*, vol 3, pp391–399

Duvick, D. N. (1984) 'Genetic diversity in major farm crops on the farm and in reserve', *Economic Botany*, vol 38, pp161–178

Evenson, R. E. and Gollin, D. (2003) 'Assessing the Impact of the Green Revolution, 1960 to 2000', *Science*, vol 300, pp758–762

Food and Agriculture Organization of the United Nations (FAO) (2011) *The State of Food Insecurity in the World*, FAO, Rome, Italy

Ford-Lloyd, B. V, Brar, D., Khush, G. S., Jackson, M. T. and Virk, P. S. (2009) 'Genetic erosion over time of rice landrace agrobiodiversity', *Plant Genetic Resources*, vol 7, pp164-168

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M. and Toulmin, C. (2010) 'Food security: the challenge of feeding 9 billion people', *Science*, vol 327, pp812–818

Goodman, M. M. (1995) 'The evolution of crop plants', pp193–202 in *Maize,* John Wiley and Sons, New York, NY, USA

Gulati, A. and Dixon, J. (2008) *Maize in Asia: Changing Markets and Incentives*, Academic

Foundation, New Delhi, India

Hawkes, J. G. (1983) *The Diversity of Crop Plants*, Harvard University Press, Cambridge, MA, USA

Hayami, Y. and Ruttan, V. W. (1985) *Agricultural Development*, John Hopkins University Press, Baltimore, MD, USA

Heisey, P. W. and Lantican, Dubin, H. J. (1999) 'Assessing the benefits of international wheat breeding research: an overview of the global wheat impacts study', in *CIMMYT 1998-99 World Wheat Facts and Trends. Global Wheat Research in a Changing World: Challenges and Achievements*, CIMMYT, Mexico CIty, Mexico

Fuglie, K. and Marder, J. (2015) ,The diffusion and impact of improved food crop varieties in sub-Saharan Africa', in T. S. Walker and J. Alwang (eds) *Crop Improvement, Adoption, and Impact of improved varieties in Food Crops in Sub-Saharan Africa*, CAB International, Wallingford, UK

Kazi, G. A., Rasheed, A. and Mujeeb-Kazi, A. (2013) 'Biotic stress and crop improvement: a wheat focus around novel strategies', pp239–267 in R. K. Hakeem, P. Ahmad and M. Ozturk (eds) *Crop Improvement: New Approaches and Modern Techniques,* Springer US, Boston, MA, USA

Krebs, J. R., Wilson, J. D., Bradbury, R. B. and Siriwardena, G. M. (1999) 'The second Silent Spring?', *Nature*, vol 400, pp611–612

Lupton, F. G. H. (1992) 'Wheat varieties cultivated in Europe', in *Changes in Varietal Distribution of Cereals in Central and Western Europe: Agroecological Atlas of Cereal Growing in Europe, Vol. 4*, Wageningen University, Wageningen, The Neatherlands

Moreta, D. E., Mathur, P. N., van Zonneveld, M., Amaya, K., Arango, J., Selvaraj, M. G. and Dedicova, B. (2015) 'Current issues in cereal crop biodiversity', *Advances in Biochemical Engineering/Biotechnology*, vol 147, pp1-35

Newton, A. C., Akar, T., Baresel, J. P., Bebeli, P. J., Bettencourt, E., Bladenopoulos, K. V, Czembor J. H., Fasoula, D. A., Katsiotis, A., Koutis, K., Koutsika-Sotiriou, M., Kovacs, G., Larsson, H., Pinheiro de Carvalho, M. A. A., Rubiales, D., Russell, J., Dos Santos, T. M. M. and Vaz Patto, M. C. (2010) ,Cereal landraces for sustainable agriculture. A review', *Agronomy for Sustainable Development*, vol 30, pp237–269

Phalan, B., Balmford, A., Green, R. E. and Scharlemann, J. P. W. (2011) 'Minimising the harm to biodiversity of producing more food globally', *Food Policy*, vol 36, ppS62–S71

Phalan, B., Onial, M., Balmford, A., & Green, R. E. (2011) Reconciling food production and biodiversity conservation: land sharing and land sparing compared', *Science*, vol 333, pp1289–1291

Pingali, P. (2010) 'Chapter 74 Agriculture Renaissance: making "Agriculture for Development" work in the 21st Century', *Handbook of Agricultural Economics,* vol 4, pp3867–3894

Pingali, P. (2012) 'Green Revolution: impacts, limits, and the path ahead', *Proceedings of the National Academy of Sciences USA*, vol 109, pp12302–12308

Pingali, P. (2015) 'Agricultural policy and nutrition outcomes – getting beyond the preoccupation with staple grains', *Food Security*, vol 7, pp583–591

Pingali, P. and Heisey, P. W. (2001) 'Cereal-crop productivity in developing countries: Past trends and future prospects', in J. M. Alston, P. G. Pardey and M. Taylor (eds), *Agricultural Science Policy*, IFPRI & Johns Hopkins University Press, Washington D.C., USA

Pingali, P. and Smale, M. (2001) 'Agriculture, Industrialized', pp85–97 in S. Levin (ed), *Encyclopedia of Biodiversity, Vol. 1,* Academic Press

Porceddu, E., C., Ceoloni, D. L., Tanzarella, O. A. and Scarascia, G. T. M. (1988) 'Genetic resources and plant breeding: problems and prospects', in *The Plant Breeding International, Cambridge Special Lecture*, Institute of Plant Science Research, Cambridge, UK

Reardon, T. and Minten, B. (2011) 'Surprised by supermarkets: diffusion of modern food retail in India', *Journal of Agribusiness in Developing and Emerging Economies*, vol 1, pp134–161

Pandey, S., Velasco, M. L. and Yamano, T. (2015) 'Scientific strength in rice improvement programmes, varietal outputs and adoption of improved varieties in South Asia', in T. S. Walker and J. Alwang (eds) *Crop Improvement, Adoption, and Impact of improved varieties in Food Crops in Sub-Saharan Africa,* CGIAR Standing Panel on Impact Assessment (SPIA), Montpellier, France

Skovmand, B. and DeLacy, I. (1999) 'Parentage of a historical set of CIMMYT wheats', p165 in *Annual Meeting Abstracts,* American Society of Agronomy, Madison, WI, USA

Smale, M. (1997) 'The Green Revolution and wheat genetic diversity: dome unfounded assumptions', *World Development*, vol 25, pp1257–1269

Smale, M. (2000) Economic incentives for conserving crop genetic diversity on farms:

issues and evidence'. Paper presented at the meetings of the International Agricultural Economics Association, Berlin, Germany

Smith, S., Bubeck, D., Nelson, B., Stanek, J. and Gerke, J. (2015) 'Genetic diversity and modern plant breeding', pp55–88 in R. M. Ahuja and M. S. Jain (eds), *Genetic Diversity and Erosion in Plants: Indicators and Prevention*, Springer International Publishing, Cham, Switzerland

Stevenson, J. R., Villoria, N., Byerlee, D., Kelley, T. and Maredia, M. (2013) 'Green Revolution research saved an estimated 18 to 27 million hectares from being brought into agricultural production', *Proceedings of the National Academy of Sciences USA*, vol 110, pp8363–8368

Tilman, D., Balzer, C., Hill, J. and Befort, B. L. (2011) 'Global food demand and the sustainable intensification of agriculture', *Proceedings of the National Academy of Sciences USA*, vol 108, pp20260–20264

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R. and Polasky, S. (2002) 'Agricultural sustainability and intensive production practices', *Nature*, vol 418, pp671–677

Trewavas, A. J. (2001) 'The population/biodiversity paradox. Agricultural efficiency to save wilderness', *Plant Physiology*, vol 125, pp174–179

Vaughan, D. A. and Chang, T-T. (1992) '*In situ* conservation of rice genetic resources', *Economic Botany*, vol 46, pp368–383

Witcombe, J. R. (1999) 'Does plant breeding lead to a loss of genetic diversity?' in D. Wood and J. Lenne (eds) *Agrobiodiversity: Characterization, Utilization and Measurement*, CAB International, Wallingford, UK