Why Do US Corn Yields Increase? The Contributions of Genetics, Agronomy, and Policy Instruments

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Abstract Much of the future quality of life will depend upon improved abilities to sustainably increase agricultural production while maintaining ecosystem services and supporting conservation of natural diversity. Some lessons for the future reside in an improved understanding of the factors that have contributed to increased agricultural productivity during recent past decades. Using US maize production as an example, we demonstrate the critical contributions of plant breeding using native maize germplasm and improved agronomic practices. We outline the policy instruments that condition successful plant breeding through determining access to plant genetic resources and by providing economic incentives for investment and innovation through intellectual property. Maximum progress in improving global agricultural production can only be made when potentially contradictory policies are implemented in a balanced fashion.

Introduction

The future of humankind depends fundamentally upon the ability of farmers to sustainably produce sufficient nutritious food. Historically, challenges to avoid the Malthusian prediction (Malthus 1798) that the demands of a growing population growth would outrun agricultural supply have been avoided by taking more land into production, by technological innovation leading to increased production per unit area, and by reductions in population growth either through choice or by decree (Food and Agriculture Organization of the United Nations [FAO] 2014).

A previous version of this chapter was published under the same title in AgBioForum 18(3):297–302.

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N. Kalaitzandonakes et al. (eds.), *From Agriscience to Agribusiness*, Innovation, Technology, and Knowledge Management, https://doi.org/10.1007/978-3-319-67958-7_6

However, challenges to maintain a sufficient and equitable supply of food and raw materials from agriculture eclipse those encountered previously. The global population is predicted to grow by more than 33% (or 2.3 billion) from 2009 to 2050 from the current level of approximately 7 billion (FAO 2009). Global food demand is predicted to double by 2050 (Tilman et al. 2011). Most good arable land is already in cultivation, so agricultural production must increase to counter a declining per capita supply of arable land. Further extension of global arable area would include taking more ecologically fragile land into cultivation and compromise environmental services provided by natural ecosystems, rivers, and forests (Foley et al. 2011). Agriculture should also contribute to an improved environmental footprint by reducing soil erosion and nutrient runoff. Crops need to remain resilient in the face of competition from weeds and persistent attacks by pest and disease organisms. And crop production must be maintained in the face of unpredictable and possibly more extreme weather.

Elucidating the factors that have contributed to increased agricultural production is the first step to understanding the elements needed to sustain future increases in agricultural production. Chief among these is the more effective use of a broader base of plant genetic resources made possible through innovative plant breeding, underpinned by improved knowledge of the genetic basis of plant physiology. We then introduce the international instruments that are in place to guide policy. We identify areas in which implementation of policies causes overreach and disruption of individual policies. We argue that the overarching public need to improve agricultural production via plant breeding is restricted when individual policies are implemented in an imbalanced manner.

US Maize Production: Disentangling the Contributing Factors to Production and Productivity

The history of US maize production can be split into three phases (Fig. 1). First, from 1866 to 1920, increased production occurred by taking more land into cultivation. Second, from 1940 to 1970, maize production further increased (Fig. 1) even as the land area used for maize cultivation shrank. Third, from the late 1980s to today, there have been increasing production and increasing area under maize cultivation. US area planted to maize in 2013 represented the highest figure since 1936, when an estimated 41.7 million ha (103 million acres) were planted (US Department of Agriculture [USDA], National Agricultural Statistics Service [NASS], US Department of Agriculture (USDA), National Agricultural Statistics Service (NASS) 2013).

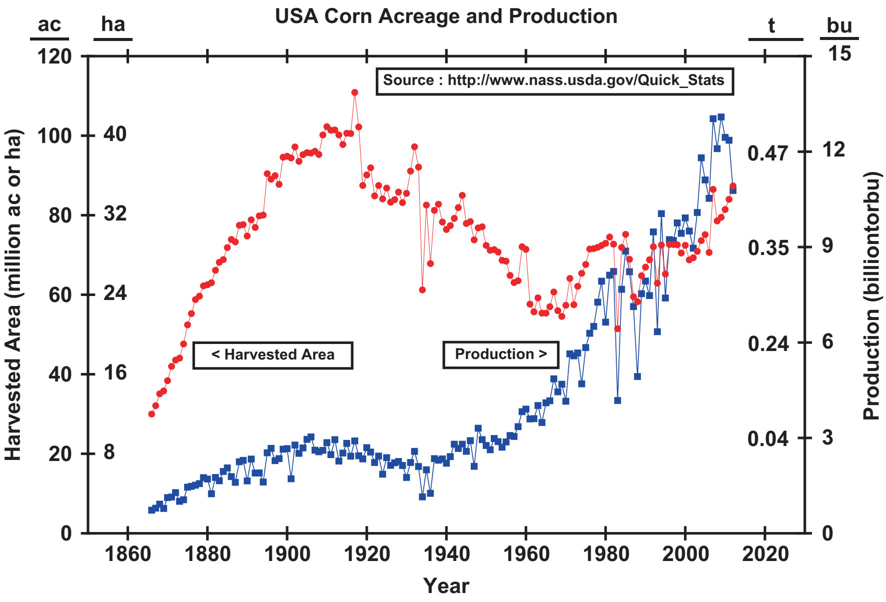

Fig. 1 US corn harvested area and production, 1865–2013 (Source: http:/www.nass.usda.gov/Quick_Stats. Reprinted with permission from Smith et al. 2014)

What Are the Factors that Have Contributed to Increasing Productivity?

Productivity is production per unit land area, i.e., yield. Examination of US maize yields from 1866 to 2011 (Fig. 2) explains the annual dynamics and interactions of land area harvested and total production (Fig. 1). From 1866 to the 1930s, maize yields approached stagnation, increasing at 3 kg/ha/yr (0.05 bu/ac/yr; Fig. 2). During the late 1930s through to the 1980s, yield increases allowed total production to increase even as land area harvested declined. From 1990 to 2011, both yields and land area harvested increased leading to record levels of US annual maize production. Factors contributing to yield must then be examined to provide a more complete understanding of their quantitative (percent contributions) and qualitative (do they interact?) aspects.

What Are the Factors that Contribute to Yield?

It is a well-established biological fact that phenotypic appearance is a result of *genotype* × *environmental effects*. Likewise, *genotype* × *environment* interactions determine yield. With regard to crop yields, numerous factors can be included

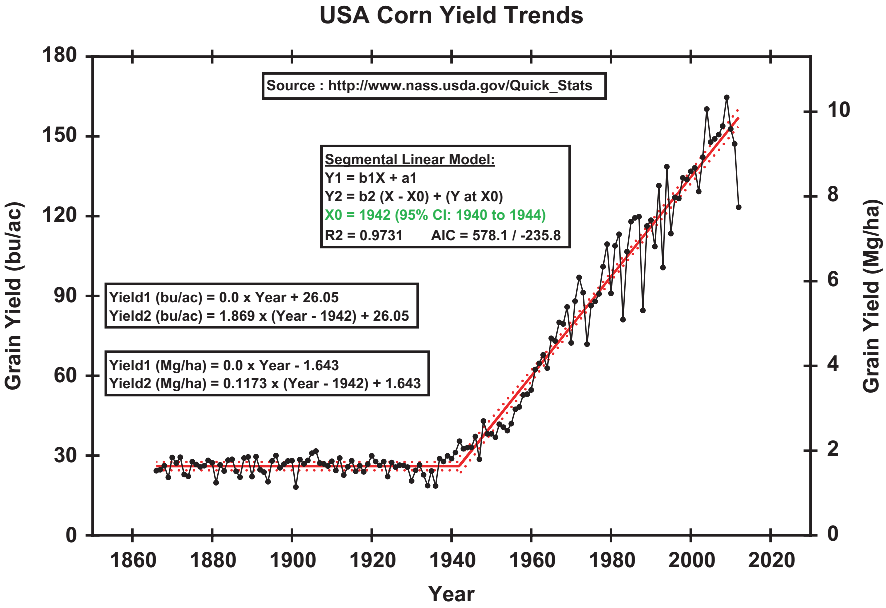

Fig. 2 US corn yields, 1865–2013 (Source: http:/www.nass.usda.gov/Quick_Stats. Reprinted with permission from Smith et al. (2014))

under the definition of "environment." These include weather, soil type, pests, diseases, and farm management practices; choice of weed, insect, and pest control methods; planting density; tillage type; planting date; and amount and dates of fertilizer applications.

How to Disentangle the Contributions of These Components to Yield

The crucial first step is to experimentally isolate and measure the genetic effects, i.e., the contribution made by plant breeders (genetic gain). Genetic effects can be extracted using sophisticated statistical analyses from yield data provided sufficient check varieties are present among a set of varieties that represent a time series of varieties according to their initial release and availability on farms. A more precise measure of genetic gain can be obtained using specially designed progress evaluation trials. Here, a series of varieties with different release dates are planted in the same environmental and farm management conditions over a series of locations and years. This is the experimental design adopted in the study reported here. Field conditions were akin to those of the target production environment (central Corn Belt) and were nonirrigated. As an additional component, we planted the hybrids at three planting rates to be comparable with current practice (high) and those employed in previous decades (medium and low). The chronological time series of hybrid release dates spanned 1930–2011. We also conducted an experiment to measure the effect on yield of adding resistance to the European corn borer (ECB) via the presence of the protein *Cry1Ab* produced by a gene extracted from the bacterium *Bacillus thuringiensis* and inserted into the maize genome by genetic engineering. For the later experiment, we used 15 pairs of hybrids grown at 3739 locations per year in 24 US states and 2 Canadian provinces over 7 years. For each pair of hybrids, the only difference was the presence or absence of the *Cry1Ab*-producing gene.

Results

The oldest hybrids performed best at low planting densities, medium-age hybrids performed best at moderate planting densities, and hybrids released since 1990 performed best at high planting densities. It is therefore most appropriate to compare yields for each hybrid when planted at its optimum planting density. These results are shown in Fig. 3. The rate of genetic gain during the period of 1930–2011 was 87.6 kg/ha/yr. (1.4 bu./ac/yr). For a subset of single-cross hybrids—which are more representative of the type of hybrid grown today and during the past five decades—the rate of genetic gain was 92 kg/ha/yr (1.5 bu/ac/yr). US maize breeders have selected for plants with greater stress resistances imposed by higher planting densities. Adaptation to those stresses includes change in leaf canopy architecture to maximize light interception and an improved ability to mine soil water and nutrients. Additional data showed more recent hybrids had reduced the flow of photosynthates to the male tassel, presumably thereby repartitioning photosynthates to the female ear, which is the site of grain production. More recently developed hybrids expressed more resistance to certain diseases and insects and were better able to retain a vertical stand.

Resistance to attack by ECB provided a mean yield advantage of 5.3% (range 2.0–5.8%). It is important to understand that ECB resistance did not increase the potential genetic gain. All potential genetic gain was generated via improvement of the native maize germplasm. Insect resistance contributed to protecting that genetic potential. During the era of single-cross hybrids, USDA data showed the rate of production gain on Iowa farms was 123 kg/ha/yr. Consequently, the contribution of genetic gain to yield gains on Iowa farms during this period was 92/123 (75%). Farm management practices accounted for the remaining 25% of yield improvement. The maximum yield that could conceivably be generated using most recently released maize hybrids and maximum input management practices was indicated by data from yield contest trials conducted under the auspices of the National Corn Growers Association. Potential yields under nonirrigated conditions were 18,599 kg/ha with a rate of yield gain of 193 kg/ha/yr. In contrast, mean maize yields on Iowa farms was 11,741 kg/ha. A vital question is how much of the yield gap of 18,599–11,741 = 6858 kg/ha can be reduced economically? The answer varies with many factors, including weather, management practices, price of fertilizer, and grain prices.

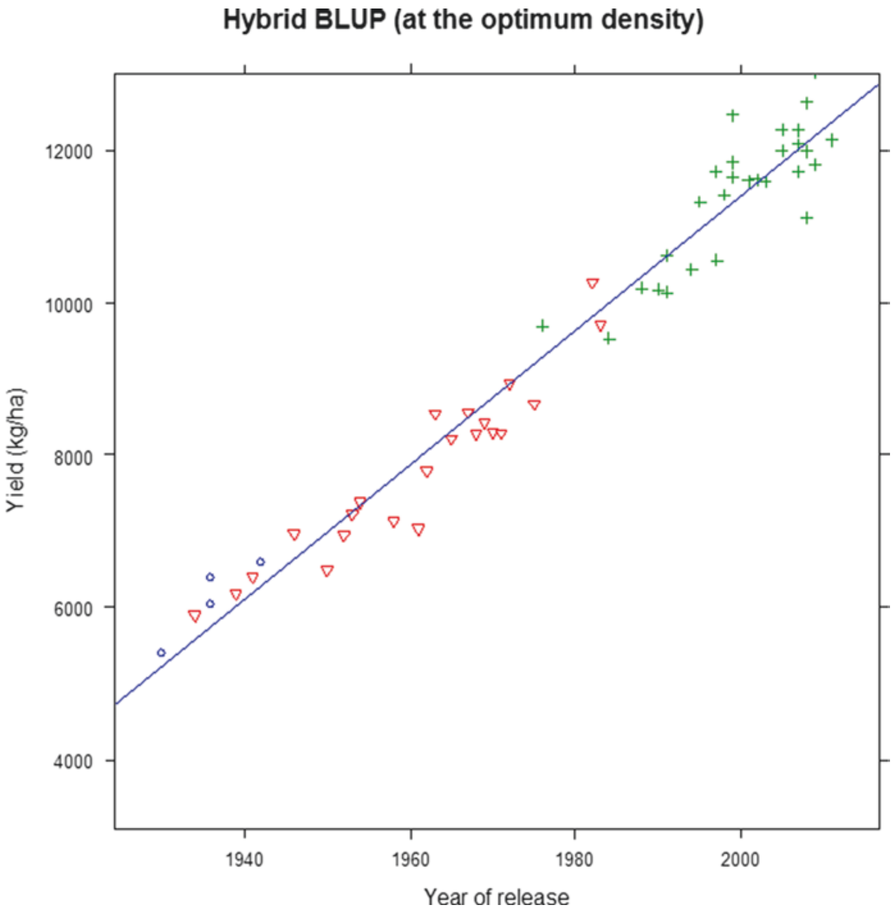

Fig. 3 Yields (Best Linear Unbiased Predictor) of Pioneer corn hybrids grown in the same environment at their individual optimum planting density (blue circles = low; inverted red triangles = moderate; green + = high) (Note: Reprinted with permission from Smith et al. 2014)

Changes in Genetic Constitution of Hybrids as a Result of Plant Breeding Associated with Genetic Gain: Genetic Diversity Change in Time

Tracking back hybrids in their pedigrees to founder parental sources enables one portrayal of change in genetic makeup as a result of plant breeding (i.e., a change in the underlying genetics that underpin genetic gain). Figure 4 shows the average founder constitution of current DuPont Pioneer maize hybrids used in the central Corn Belt. In comparison, farmers in this region in the decades before the 1930s were largely growing Reid Yellow Dent—a genetic source which now only contributes 24% of the genetic background—thus exemplifying the integration of different

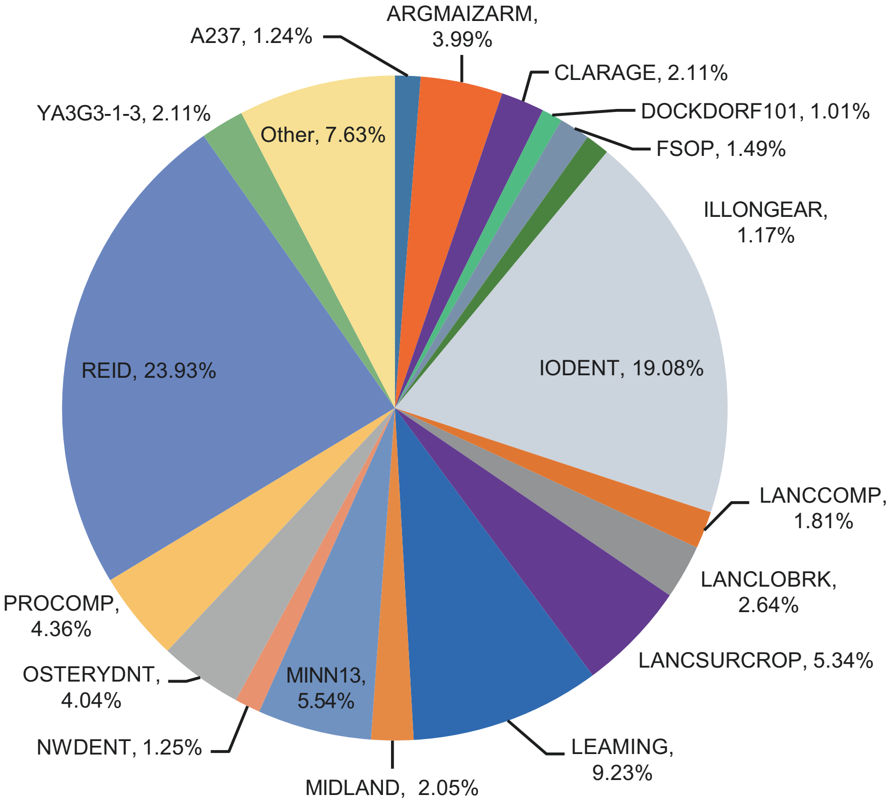

Fig. 4 Mean landrace or founder contribution by pedigree to Pioneer corn hybrids released 2000–2009 (Note: Reprinted with permission from Smith et al. (2014). Most farmer landrace saved-seed varieties cultivated in central Iowa during the late nineteenth century and 1900–1930 were Reid Yellow Dent which now represents only 24% of the pedigree background, showing an increase in genetic diversity)

genetic diversity, primarily at least during the past 2000–3500 years, from other regions that are now within the borders of the United States. Figure 5 shows genetic change in time of chromosomal segments due to plant breeding.

Valuation of Increased Productivity

Comparing the land required to produce the 2013 US level of corn production using the hybrids and management practices of earlier eras is illustrative of both the economic and environmental importance of improving productivity. For example, if the entire state of Iowa was planted with corn—including land that is now under concrete or under water—then it would require 2.4 Iowa states to produce the entire

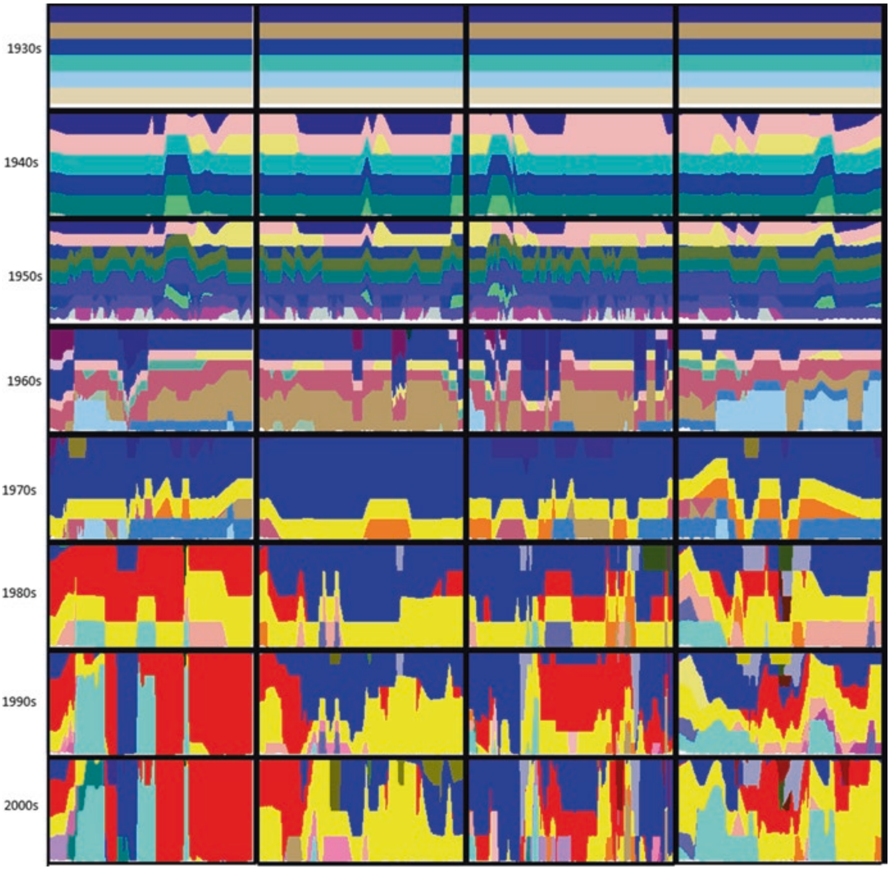

Fig. 5 Change in decadal genetic diversity of corn hybrids from the 1930s to the 2000s (Note: Reprinted with permission from Smith et al. (2014). Comparison of four of the ten diploid chromosomes. Changes in color denote different genetic segments along each of the four chromosomes (horizontal) tracked by molecular markers and DNA sequence. Note the huge changes during the 1960s and 1970s, with changes continuing during subsequent decades)

2013 US corn crop using 2013 genetics and farm management practices. If maize hybrids and farm management practices of the 1980s were used, then it would require 3.6 Iowas. And if maize hybrids and farm management practices from the 1930s were used, it would require 14.5 Iowas. There is also an increased environmental valuation of increased productivity as genetic inputs replace chemical inputs; these include providing insect or disease resistance, having a requirement for less use of fuel for cultivation, contributing to soil conservation, or making more effective use of fertilizer or water resources. As contributions from chemical inputs plateau or decline, then there will be an increased dependence upon productivity gains and in contributing to a cleaner environment through the use of plant genetic resources via plant breeding.

Access to and Use of a Range of Genetic Diversity: The Policy Arena

Access to a useful range of genetic resources and an increased ability to effectively utilize those resources in plant breeding will be ever more critical components of helping to achieve a more sustainable, environmentally friendly, and productive agriculture system. Critical policy areas that come into play in helping to promote more effective agriculture as a result of plant breeding are those dealing with terms of access to germplasm and the ability to obtain intellectual property protection (IPP). International treaties can be, and usually are, modified on a country and regional basis. This leads to a highly complex international landscape for IPP and access and benefit sharing (ABS) with regard to plant genetic resources for food and agriculture.

Four treaties are the most relevant in this respect. First, the World Intellectual Property Organization (WIPO), a specialty agency of the United Nations, was created in 1967 with the goal "to encourage creative activity, to promote the protection of intellectual property throughout the world" (WIPO 1967). WIPO has 188 member states.[1] The Patent Cooperation Treaty (PCT)[2] is an international patent law treaty, signed in 1970, that provides a unified procedure for filing patent applications in 148 countries. WIPO and the PCT seek to incentivize innovation primarily through the grant of patents, trademarks, and industrial designs to eligible subject matter. A primary incentive is to make information about an invention public via a patent in exchange for an exclusive right for a temporal period. WIPO members also examine how to protect traditional knowledge and folklore related to genetic resources.

Second, the International Union for the Protection of New Varieties of Plants (UPOV) was established as an intergovernmental organization in 1961 and revised in 1972, 1978, and 1991. UPOV provides specialist or "sui generis" intellectual property rights for plant breeders who develop varieties that are distinct, uniform, and stable. UPOV's mission is to provide and promote an effective system of plant variety protection (PVP), with the aim of encouraging the development of new varieties of plants for the benefit of society—provided breeders have exclusive rights to sell their variety. However, unlike patents, PVP does not restrict unlicensed further breeding of a protected commercialized variety. However, if the new variety is determined to be essentially derived (UPOV of 1991) from the initial variety, then the owner of the initial variety retains ownership of the essentially derived variety. As of June 10, 2014, there were 72 UPOV members.[3]

Third, the Convention on Biological Diversity (CBD) was opened for signature at the Earth Summit in Rio de Janeiro in 1992 and entered into force in December 1993. The CBD seeks to achieve the conservation and sustainable use of biological diversity coupled with the fair and equitable sharing of the benefits arising out of the utilization of genetic resources. There are 195 parties to the CBD.

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[1] See http://www.wipo.int/members/en

[2] See http://www.wipo.int/pct/en

[3] For the full list, please see http://www.upov.int/export/sites/upov/members/en/pdf/pub423.pdf

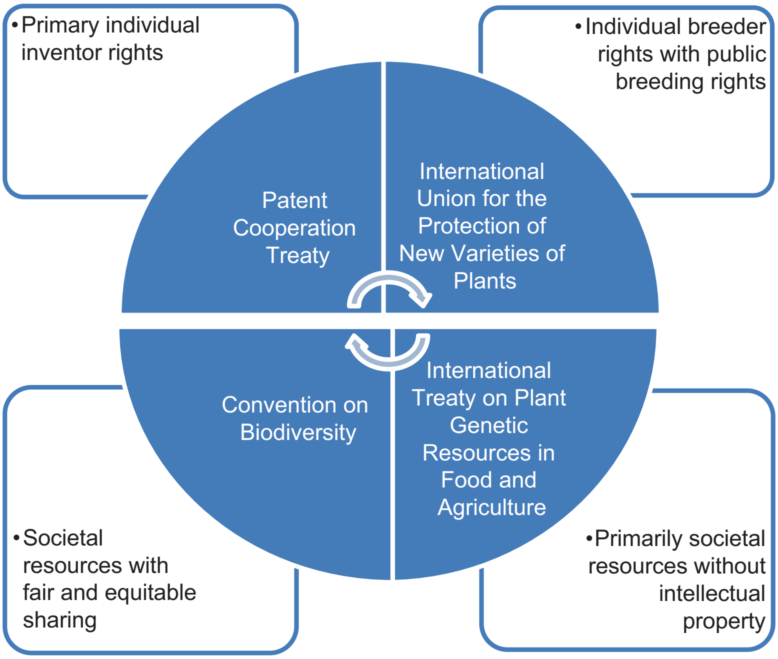

Fig. 6 The four treaties that impact access to plant genetic resources and finance, risk-taking, innovation in research, and product development with regard to plant breeding (Note: Two treaties (Patent Cooperation and the International Union for the Protection of New Varieties of Plants) are designed to incentivize investment in innovation, and two (The Convention on Biological Diversity and the International Treaty on Plant Genetic Resources for Food and Agriculture) are designed to conserve and facilitate use of genetic resources while respecting and supporting society)

Fourth, the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) recognizes the contribution of farmers to the diversity of crops that feed the world. It establishes a global multilateral system to provide farmers, plant breeders, and scientists with access to plant genetic materials and seeks to ensure that recipients share benefits they derive from the use of these genetic materials with the countries from which they were sourced. The CBD (from December 1993) brought the jurisdiction of genetic resources under national sovereignty. The treaty was developed as a comprehensive international agreement in harmony with the CBD because of the special and distinctive nature of agricultural genetic resources, including thousands of years of pedigree histories crossing countries and continents and because of their international importance for global food security. The ITPGRFA entered into force in June 2004 and currently has 193 contracting parties.[4]

These four treaties are presented in Fig. 6 in such a way to emphasize both the nature of their individual and collective or complementary underlying public policies. Two treaties (WIPO with PCT and UPOV) are designed to incentivize

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[4] See the list of parties at http://www.planttreaty.org/list_of_countries

investment in innovation, whereas the other two treaties (CBD and ITPGRFA) are designed to protect societal resources. Collectively, each of the four treaties has the public policy of increasing social welfare, albeit through some degree of competing interests. Consequently, unbalanced implementation may lead to a loss in overall social welfare that an otherwise more balanced implementation could have supported. For example, an encroachment of CBD onto the ITPGRFA could result in reduced access to germplasm for further breeding and thus have a net negative effect on increasing agricultural productivity. Achieving a balanced approach can lead to the protection of societal resources while incentivizing the innovation required to increase crop yields. These treaties can be viewed as a matrix according to their policy goals (Fig. 6).

Ideally, policy goals should be individually and collectively directed toward achieving the common public goal of improving global agricultural production, i.e., working complementarily and synergistically. However, overall opportunities are lost when implementation of one treaty expands and overreaches, thereby stifling the positive goals of another treaty. For example, implementation of biodiversity laws by some countries has reduced or halted international flows of germplasm and undermined the policy goals of UPOV to allow further breeding with commercialized varieties. Likewise, overreach of patent protection can reduce short-term spread of newly developed germplasm. Or a lack of effective legal instruments to provide time-limited IP can result in greater dependence upon the use of trade secrets, which undermines dissemination and use of new knowledge or germplasm. We understand at least some of the complexities and political challenges in raising the common global good above national or more parochial interests. Nonetheless, given the crucial importance of plant breeding and agriculture to improving lives and livelihoods while also contributing to improved environmental health and ecosystem sustainability, we consider it important that the greater global and public good be always kept in mind as the ultimate goal to achieve.

Acknowledgments Figures 1,2, 3, 4, and 5 are reprinted with permission from Smith et al. (2014).

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