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未来作物育种对绿色技术的需求

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摘 要 未来的作物育种涉及多方面的问题。本文主要就与粮食安全紧密相关的问题进行探讨,包括对粮食产量和品质的需求,以及粮食生产的可持续发展。当今,我们同时面临食品需求和可持续发展两大挑战,既要求在未来几十年实现大幅度增产以满足人口快速增长的需要,又要降低化肥、杀虫剂、水资源以及劳动力等各种资源的投入来确保可持续发展。此外,越来越多的人开始注重与健康直接相关的食品营养,这又对培育高品质的粮食作物提出了新的要求。解决这些问题是作物育种的追求和目标。本文将对近期研究者在这方面的努力做一综述,不仅包括植物基因组学研究和相关技术的发展,还将讨论这些工作在育种过程中的应用,以探讨粮食安全问题的解决途径。

关键词 粮食安全;可持续发展;基因组学;转基因;育种目标

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在过去特别是20世纪,作物育种对粮食产量的增长做出了巨大贡献。以1966年至2000年为例,人口密集型低收入国家在这些年人口增长近100%,但粮食产量足足增加了125%。人类近万年努力使得1960年的粮产达到10亿 t,但只过了40年,2000年世界粮产已突破20亿 t[1]。这一成就很大程度需要归功于培育出并广泛种植遗传改良品种的“绿色革命”。

进入新世纪,展望未来,人们对粮食产量的需求继续攀升,同时还将面对空前的环境压力。诸多新兴植物科学技术的诞生让人不至于特别沮丧,这些前沿的科技为我们提供了理论和方法来培育新的品种以应对上述种种困难。

本文将对当今粮食需求现状、自然环境压力、植物科学研究进展以及如何利用新的科技解决粮食安全和可持续发展等问题一一阐述。

1 什么是粮食安全

粮食安全的概念应考虑两个方面:即粮食产量需求和粮食生产的可持续发展。下面主要以中国为例对这两个问题进行简要阐述。

1.1 粮食总量需求

世界人口在2012年突破72亿,预计到2050年将达到96亿,并在2100年进一步增长到109亿[2]。联合国粮食与农业组织(FAO)预计世界粮食总产量需求在2050年比2007年增长70%(在发展中国家增加100%)才能满足世界人口增长40%的需要,保证每人每天获得3 130千卡能量[3-5]。这就需要粮食产量每年保持增长1.2%。其中的90%(发展中国家为80%)增长将来自于提高产量、增加种植密度以及增加耕地面积。

基于1960年以来人均从作物中获得的热量及蛋白等成分与人均GDP的关系,Tilman等人[6]预计到2050年人们对来自作物的热量需求将比2005年增加1倍,而对蛋白的需求更是增加110%。这种预测需要粮食年产在此后每年增加1.5%～1.6%,这一比例高于过去10年绝大多数农产品的增长率,主要的粮食作物更是如此[3]。

对于中国来说,其人口总量预计从2012年的13.86亿增长到2025年的14.49亿,并将于2050年回落至13.85亿[2]。基于人口、城市化、收入的增长和消费趋势这四大要素,对中国农产品未来需求

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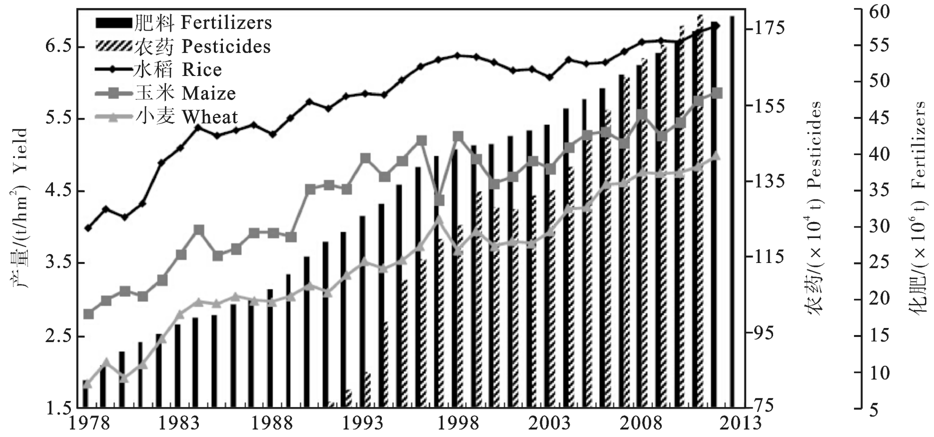
的预测表明[7]，至 2050 年，人们食品消耗的总值将比 2009 年增长 104%，其中对谷物的需求增长为 52%，即每年增长 1%。

1.2　生产的可持续性

本文将就我国面临的资源和环境问题对这一话题进行阐述。过去的 50 年，许多农产品的总产量都得到了大幅度提高，包括水稻、小麦和玉米这三大主要粮食作物在内。具体来说，由 1961 年至 2000 年水稻的产量增加了 3 倍，小麦和玉米更是增长了 5 倍以上[8]，这使得我们创造了以全世界 8%～9% 的耕地养活世界 20%～25% 人口的奇迹。

当然，取得这一成就的代价也是巨大的（图 1）。最近几年，我国年消耗化肥 5 500 万～6 000 万 t[9]，超过了世界化肥消耗的 1/3[5]（在 2009 年全世界共消耗 1.72 亿 t）。每年农药的消耗量也占全世界的 31%，比如 2005 年，全世界共消耗 460 万 t，而我国就高达 146 万 t[10]。我国每 667 m^2 耕地使用的化肥和农药超过世界平均水平的 4 倍，这带来的恶劣后果就是土地、大气、水源以及农产品本身的严重污染，并进一步危害人们的身体健康。

另一方面，尽管一直过度使用化肥和农药，但过去几年主要粮食作物产量的增长却遇到了瓶颈（图 1）。其原因在于过度使用化肥不仅破坏环境，而且降低土壤质量；滥用农药不仅未有效控制病虫害，反而增加病原菌和害虫的耐药性，进而带来越来越高频的病虫害爆发。



数据来自国家统计局（2014-09-15）（http://www.stats.gov.cn/）.

图 1　中国 1998 年至 2012 年水稻、玉米和小麦的产量以及相应的化肥、农药投入

Fig. 1　Yields of rice, maize and wheat during 1998－2012 compared to the total consumption of fertilizers and pesticides in China

展望未来，我国农产品的增长形势严峻，从资源和环境的角度讲，主要包括以下 3 个限制性条件。

第一是耕地面积。尽管全世界可耕作土地预计会自 2007 年的 15.48 亿 hm^2 小幅增长至 2050 年的 16.61 亿 hm^2，但我国将相应地由 1.3 亿 hm^2 降至 1.22 亿 hm^2[5]，这意味着要在更少的土地上生产更多的粮食。

第二个约束因素在于投入的困境，包括化肥和农药等的使用。预计在 2050 年全世界总化肥使用量为 2.63 亿 t[5]，而我们近几年的年消耗在 6 000 万 t 左右，已经达到了 2050 年总量的 23%；再加上不断恶化的环境，已经没有更多的余地让我们增加化肥的使用量了。农药的使用面临同样的困境。

最后一个是我国人均淡水资源仅为世界的1/4，旱灾在许多地区频发，对农业构成了巨大威胁，自古以来一直如此[11]。

因此，粮食产量的可持续发展就成了满足未来需求的先决条件。

2　育种目标在解决粮食安全问题中的演进

2.1　“第二次绿色革命”的定义

在 20 世纪 90 年代末，我国科学家就意识到了

提高农产品供应与节约资源、保护环境这一矛盾，并提出了“第二次绿色革命”的概念以作为科学研究和作物改良的导向和目标，其主旨可概括为：少投入、多产出、环境友好[12]。

2.2 主要作物育种策略必须做深刻的改变以实现产量潜力

育种在过去很长的一段时间是单一追求粮食产量，导致“耐肥、抗倒伏”成了育种最理想的性状。很多新品种试验都在高肥力、灌溉良好并精心管理的条件下进行，这忽视了我国2/3的耕地属于“中-低产土田”[13]这一基本情况，使得通过试验的高产品种并不适合在大部分土地种植，无法实现其期待的产量潜力。这在很大程度上造成过去几十年农民种植得到的实际产量和预期有很大的差距。因此，我们需要改变育种策略，以提高在“中-低产土田”上的实际产量。

2.3 农业生产的可持续应是现代育种目标的主要内容

为实现可持续的粮食生产，育种策略需要做大的变革，以实现节约资源和保护环境。重视农业生产的可持续发展，意味着减少资源投入，包括大幅减少化肥、农药、灌溉用水、劳动力及其他资源。这就要求新培育的作物品种除了产量和品质优良之外，还需具备多种生物胁迫的抗性——包括抗主要病虫害，以及非生物胁迫抗性，如干旱、盐碱、极端温度等不利条件。为了降低化肥消耗，新培育的品种应能高效利用土壤中的营养，包括氮、磷、钾等。

2.4 绿色超级稻案例

实现上述育种目标的一个例子就是由中国科学家提出的“绿色超级稻”[14]的理念，同时针对解决粮食需求和可持续发展的难题。绿色超级稻是旨在培育“少打农药、少施化肥、节水抗旱、优质高产”的水稻新品种。因此，绿色超级稻需要拥有这几方面特性：在不同的水稻产区对主要病虫害具有抗性、高效利用土壤氮和磷等营养元素、耐干旱等多种逆境。显而易见，培育绿色超级稻在技术上来讲比常规育种要复杂得多。不仅如此，更大的挑战还在于培育绿色超级稻以及其他的绿色超级作物还需要好的社会舆论氛围以及政府政策的支持和鼓励。我国政府已经宣誓到2020年建成“资源节约型、环境友好型”的农业体系。尽管我们在植物科学研究和绿色超级稻培育的技术层面已经有了长足进步，迄今为止在社会建设和公众认知方面的进展却甚为有限。

2.5 育种目标的进一步扩展

随着科技知识的累积普及和人类社会的发展，人类社会对食品于人类的作用期待也会演变。因此，对包含主要谷物在内的农作物育种目标也要相应变化才能同时满足未来生产者和消费者的需求。

从消费者角度来说，农产品不仅提供基本的能量，也需要提供更多的营养以保证身体健康。例如，国际项目HarvestPlus的主要任务就是通过提高农作物中铁、锌元素和维生素A含量来满足消费者特别是发展中国家的消费者对营养元素的需求[15]。其他植物营养素，如抗氧化物[16]和抗性淀粉[17]也已经被视作对人体健康有利。因此，作物科学研究和育种就要考虑增加这些有利人体健康的植物营养成分，这就是“生物强化”的目标。

另一方面，降低劳动力投入、实现机械化生产和降低田间管理成本已经成为包括我国在内的诸多新兴经济体在城市化进程中需要面对的新问题。以水稻为例，上述要求就需要水稻新品种有利于直播、机械化插秧和收获；此外，还需要耐除草剂、降低种子成熟期水分含量以达到降低田间管理和种子干燥所需成本的目的。所有这些和上述“少打农药、少施化肥、节水抗旱”的绿色性状一起，可以很大程度降低生产成本，为农民带来巨大实惠。

3 后基因组时代的作物育种

3.1 基因组研究

如今的数据库包含大量的基因序列等基因组信息。人们已经可以获得水稻和玉米的高质量参考基因组序列，许许多多其他作物的基因组序列草图也逐渐公布。在此基础上，大量品系的重测序为很多研究领域奠定了基础，包括全基因组关联分析以及等位基因发掘。

以发掘基因组功能为主旨的作物功能基因组研究方面也取得了很大进展。还是以水稻为例，水稻功能基因组计划已经开发了可用于高通量基因功能研究的技术和资源库：以T-DNA和转座子插入以及物理化学诱变等技术构建的超大突变体库、多品种多组织的转录组测序数据、水稻两个主要亚种（籼稻和粳稻）的全长cDNA测序数据、具有丰富多样

性种质资源的代谢组数据以及包括野生稻和栽培稻在内的数千个品种的基因组测序数据。所有这些资源都可以加快水稻基因克隆和功能鉴定的进程。过去的数十年中，科学家已经克隆了数百个基因并阐明其功能，近几年这一步伐逐渐加快[18-19]。

3.2　基因组育种

基因组学研究的进步使得基因组育种正在成为现实。基因组育种主要包括两个方面：全基因组设计和基因组工程。当然，这两项技术都还需要很长时间的进一步完善。

1)全基因组设计。Zhang 等[18]描绘了全基因组设计育种的框架，其主要包括 4 个不同层次(这里略有修改)：①通过设计出在给定生态条件下最大限度利用太阳能的群体结构能达到的产量极限；②设计出符合这一群体结构的理想株型；③不同的育种目标所要求的株型构成、优质、高效利用土壤营养、抗多种生物及非生物逆境及其他性状；④形成这些性状的基因和调控网络。很清楚，品种设计的能力有赖于我们对基因和基因组调控网络的了解，以及大量新技术的发展。

2)基因组工程。育种过程本身就与工程有许多相似之处，根据目前的发展和理解，基因组工程主要包含下面这几项具体的技术：全基因组预测、全基因组选择、基因编辑和转基因。

①基因组预测。基因组预测的复杂性依育种目标而异。对于改良如由主效基因控制的抗病性这类性状情况相对简单，即便不用复杂的预测方法，其预测能力依然很高。但对于诸如产量和杂种优势这种复杂性状，就需要较复杂的预测方法，这不仅是提高选择效率所必需的，对全基因组设计也至关重要。近年来，借助基因组重测序得到的基因型和田间试验对多种表型的测定而开发的预测模型有了长足发展[20]。来自其他组学的数据，比如转录组、蛋白组和代谢组等，也可能对表型预测很有用处。对多个组学以及农艺性状间关系的剖析将可能促进作物系统生物学的发展，并进一步辅助预测和设计。

②基因组选择。基因组选择是在分子标记辅助选择基础上的自然拓展。受益于高通量测序技术的发展，我们可以掌握全基因组更多 DNA 多态性信息，加之对基因的遗传、功能和表型效应信息的最大化利用，基因组选择可以针对特定育种项目对目标(基因和表型)、非目标以及全基因组背景同时进行选择。

基因组选择的精确性需要两方面关键技术：全基因组水平低成本的基因型鉴定和针对单个基因的特异性选择系统。基于大规模重测序得到的多态性来设计的芯片已经在多种作物的育种项目中[21-22]得以充分使用，可以用来精确鉴定遍布基因组中的成千上万的多态性核苷酸亲本来源，以及子代个体中的重组位点。基因特异的选择体系包括两部分：利用位于目标基因内的功能标记进行正向选择；利用与目标基因紧密连锁的两侧标记来进行反向选择。这 2 种技术的结合可成为一个强大的选择工具，在避免连锁累赘的情况下将基因精确导入优良品种中，以此构建近等基因系或者所需要的变异品系。这项策略可能特别适用于多系品种的培育，以获得田间的持久抗性。

③基因编辑。近年来多种基因编辑技术得到了迅速发展，包括 ZFNs、TALENs 和 CRISPR/Cas9[23]。如今，对基因序列进行修饰特别是产生功能缺失突变已经可以实现。功能基因组研究已揭示作物中许多优良的性状受隐性基因控制，这种基因修饰技术大有应用前景。基因编辑技术的进一步发展将会使序列修饰变得更容易，可以容易地实现功能缺失型和功能获得型两种修饰。这将开启作物育种的新范式。

④转基因技术。转基因作物的研发和大规模应用对作物育种、种业和作物生产都产生了巨大影响。在未来育种中，转基因技术将至少在这几方面担当不可替代的作用：(1)引入作物中本没有的性状，比如将芽胞杆菌的基因导入作物中以提高抗虫能力，这已经带来了巨大的经济和环境效益；(2)针对受多基因调控的通路，比如维生素 A，这对改善全球许多地区人们的营养状况也具有很大潜力；(3)通过一次转基因事件导入多个基因同时改良多个性状，例如 SmartStax[24]就实现了同时对昆虫和除草剂具有广谱抗性。

3.3　技术与种业的整合

搭建先进技术平台并充分利用前沿科技的能力很大程度上取决于种业的发展。尽管每一个单项技术都能在一定程度上对育种做出贡献，但将这些不同的技术与大田育种相整合，才能发挥其巨大的威力，发挥出效应。然而，实现这种整合将需要基础设

施、设备、人力资源的巨大投资和类似于大型种子公司而不是小作坊的团队合作。尽管在类似中国这样的发展中国家的作物科学研究已经有了非常大的发展，但种业在这些国家依旧薄弱。

在中国，政府通过鼓励种子公司大力发展科研能力培育自己的育种计划来加强种业，并支持利用最新基因组学研究成果和生物技术来进强化育种。显然，这种发展模式距离工业规模并对农业生产产生重大影响还任重道远。

4 展望

随着人口增加、人们生活水平的提高以及愈来愈严峻的资源、环境压力，育种目标也应随之变革以满足人们对能量、营养乃至环境可持续发展等诸多要求。作物育种需要充分考虑包括个体农民在内的小型生产者群体的利益，通过改变田间管理方式降低劳动力、降低资源投入、实现机械化来大幅度提高作物生产效率。随着植物科学研究和基因组技术的发展，作物育种将更加基于宽广、坚实的前沿科学。同时，科学和技术的发展使得人们能更有效率地利用包括目前仍未开发的远缘物种在内的多样的种质资源。信息科学、生物信息学和系统生物学也将在未来的作物育种中扮演重要角色。此外，育种活动的全球化和商业化趋势已然不可逆转，并将持续作为引擎推动种子产业和育种科技的发展。

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Demands for green technologies in future plant breeding

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Abstract Many issues need to be dealt with for future plant breeding. In this paper, I briefly discussed issues related to the concept of food security from the perspective of total demand both in quantity and quality and production sustainability. We are now facing great challenges in both demand and sustainability. Food production needs to be greatly increased in the coming decades to cope with the population explosion, while the environmental sustainability requires reduction of input including chemical fertilizers, pesticides, water, labor and other resources. Increased awareness of the relation between nutrition and health also requires crop products to better meet the need of human population by producing more nutritious food. The goals and directions of plant breeding have to evolve accordingly to address all these needs. To this end, I briefly reviewed the recent progress in plant genomic research and technology development and discussed how these advances can be applied to breeding programs to address food security issues.

Key words food security; environment sustainability; genomics; transgenics; breeding goals

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Demands for green technologies in future plant breeding

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Abstract Many issues need to be dealt with for future plant breeding. In this paper, I briefly discussed issues related to the concept of food security from the perspective of total demand both in quantity and quality and production sustainability. We are now facing great challenges in both demand and sustainability. Food production needs to be greatly increased in the coming decades to cope with the population explosion, while the environmental sustainability requires reduction of input including chemical fertilizers, pesticides, water, labor and other resources. Increased awareness of the relation between nutrition and health also requires crop products to better meet the need of human population by producing more nutritious food. The goals and directions of plant breeding have to evolve accordingly to address all these needs. To this end, I briefly reviewed the recent progress in plant genomic research and technology development and discussed how these advances can be applied to breeding programs to address food security issues.

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1 Introduction

Plant breeding has made great contributions to the increase of food production especially in the past century. For example, in the period from the year 1966 to 2000, the population of densely populated low-income countries increased by almost 100%, but the food production increased by 125%. It took almost 10 000 years for food grain production to reach 1 billion tons in 1960, and only 40 years to reach 2 billion tons in 2000[1]. This achievement is largely credited to the "green revolution" of developing and widespread adoption of genetically improved varieties.

Entering the new century and looking into the future, the demand for increasing food production continues to increase. However, environmental pressure is more intense now than anytime in the history. On the bright side, there have been tremendous advances in plant science research and technology development, which may provide knowledge and technology to help plant breeding to cope with the issues by providing new crop varieties.

The objective of this paper is to provide an overview on the current situations of food demand, environmental pressure and technology development in plant science research, and discuss how science and technology can be translated to address the issues of food demand and sustainable production.

2 The concept of food security

Two requirements have to be addressed for food security:the total demands and sustainability of the production. I will address these two issues briefly with the focus on the scenario in China.

2.1 Food demand

The world population was 7.2 billion in mid-2012 and is projected to reach 9.6 billion in 2050 and further increase to 10.9 billion in 2100[2].

FAO projected that the aggregate volume of world agricultural production needs to increase by 70% (nearly 100% in developing countries) by 2050 compared with 2007 to cope with a 40% increase in world population and to raise average food consumption to 3 130 kcal per person per day[3-5]. This requires an increase of the production by 1.2% per year. Ninety percent (80% in developing countries) of the growth in crop production would be a result of higher yields and increased cropping intensity,with the remainder coming from land expansion[4].

However, Tilman et al[6], based on the relationship between per capita demand for crops measured as caloric or protein content of all crops combined and per capita real income (GDP) since 1960, forecasted

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that global demand for crop calories would increase by 100% and global demand for crop protein would increase by 110% from 2005 to 2050. This forecast would require the global increase of crop yield to be 1.5%-1.6% per year, which is higher than the progress that has been realized in the last decades for most of the commodities, especially the major cereals[3].

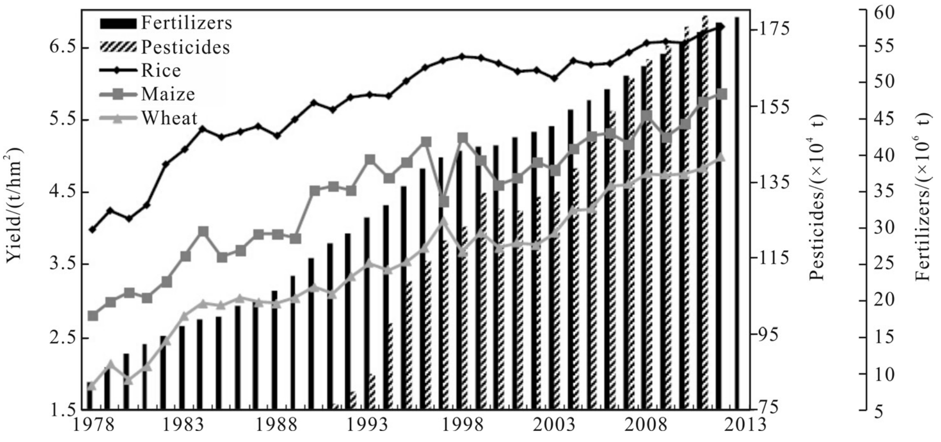
The population of China is projected to increase from 1.386 billion (2012) to 1.449 billion by 2025 and declines to 1.385 by 2050[2]. The demand of China for agricultural products to 2050 has also been predicted[7], based on four main drivers for food demand: population, urbanization, income growth and consumption trends. According to this prediction, the real value of food consumption in China will increase by 104% between 2009 and 2050, of which the demand for cereals will increase by 52%, approximately 1.0% per year.

2.2 Sustainability of production

I will address this issue mainly based on the scenario of China from the perspective of resource and environment. In the past half century, there has been great increase in total production and yields of many major commodities, including the three major cereals, rice, wheat and maize. For example, rice yield increased more than three times from 1961 to 2000, and the yields of wheat and maize increased more than 5 times[8]. Consequently, China has created a miracle of feeding 20% to 25% of the world population with only 8% to 9% of the arable land.

The cost, however, is huge (Fig.1). In recent years China has been continuously consuming 55-60 million tons of chemical fertilizers annually[9], which accounts for more than a third of total fertilizers (e.g.172 million tons in 2009) consumed globally[5]. Similarly, China has also been consuming 31% (1. 46 million tons in 2005) of the 4. 6 million tons pesticides produced worldwide[10]. Thus on a per unit area basis, China uses>4 times of the global average of fertilizers and pesticides, which has created widespread pollutions in soil, air, water and crop products. Such pollutions also cause hazards related to human health.

Despite the excessive uses the fertilizers and pesticides, the yield increase for major crops has leveled out over the last decade (Fig.1). In addition to environmental damage, heavy use of fertilizers has caused deterioration of soil quality and crop productivity. Pesticides have not been effective in controlling the insects and diseases, and instead, heavy uses have increased the frequencies of outbreaks of major diseases and insects, due to development of resistance to the pesticides in the pathogen and insects populations.



Data from the State Statistical Bureau of China (http://www.stats.gov.cn/) accessed September 15, 2014.

Fig.1 Yields of rice, maize and wheat during 1998-2012 compared to the total consumption of fertilizers and pesticides in China

Looking into the future, the constraints to further increase of agricultural production in China are severe. From the perspective of resource and environment, there are three major ones.

The first constraint is the arable land. It was estimated that China had 130 million ha arable land in 2007, and would reduce to 122 million ha by 2050, despite that the total arable land of the world is projected to expand slightly from 1 548 million ha to 1 661 million ha during this period[5]. Thus much more has to be produced in less land in China.

The second constraint is perceived as the dilemma in input use, especially fertilizers and pesticides. For example, the total global fertilizer production is projected to be 263 million tons in 2050[5], while the current amount of ~60 million tons used in China in recent years already makes 23% of the projected global total in 2050. Clearly, there is no room for China to further increase fertilizer production and application in the future, especially with the already heavily polluted environments. The same is the case for pesticide use.

In addition, the per capita water resource of China is only a quarter of world average. Drought frequently occurs in many parts of China and has been a major threat to agriculture for centuries[11].

Thus, sustainability of the agricultural production has to be addressed as a high priority in order to meet the future demand.

3 Evolving breeding goals to address food security

3.1 Our definition of “second green revolution”

In the late 1990s’, Chinese scientists already perceived the potential conflict of agricultural production with resource and environment and proposed the notion for a “second green revolution” in agriculture with the key words:less input, more production and better environment, as the goal for plant science research and crop improvement[12].

3.2 The breeding strategies of major crops should be drastically modified for achieving potential yield

For quite a long time, the breeding goals for major crops have been dominated by yield increase. In major cereals, “fertilizer-tolerance and lodging resistance” has been regarded as a desirable trait of breeding. Varietal tests for certification have been conducted in fields of high fertility with irrigation and good management. However two-thirds of agricultural land in China belong to the categories of “medium-to-low yielding lands”[13], where varieties released based on test data from favorable conditions do not fit and it is not possible for these varieties to realize the yield potential under such conditions. This explains a large portion of the yield gap between the yield potential of the released varieties and the real yield in farmers’ field in the past decades. Modification of breeding strategies is strongly recommended to address improving productivity of the “medium-to-low yielding lands”.

3.3 Sustainability should be a major part of the breeding goals

Substantial modification should also be endorsed to the goals of future breeding to address sustainability, in order to achieve resource saving and environment protection. For sustainability of agricultural production, crops should be produced with less input, including great reduction of fertilizers, pesticides, water, labor and other resources. This requires crop varieties to possess resistances to multiple biotic stresses such as major diseases and insects, and abiotic stresses such as drought, salinity, extreme temperature and other unfavorable conditions, in addition to yield and quality. To reduce fertilizer consumption, new varieties should also have improved nutrient-use efficiency, including nitrogen, phosphorus and potassium, at the least.

3.4 The case of Green Super Rice

An example of such new breeding goals is the notion of “Green Super Rice” (GSR) that addresses both the demand and sustainability, proposed by rice scientists in China[14]. GSR aims to produce more rice of good quality to meet the consumers’ demands with reduced consumption of fertilizers, pesticides, and water. Thus the new rice varieties should possess the following traits: resistances to major insects and diseases in various rice producing regions, improved N-and P-use efficiency, and resistance to drought and other environmental stresses in areas needed. Clearly the science and technology involved in the development of GSR are more comprehensive than the ordinary rice breeding programs. Even more challenging is the need for societal environment and governmental policy to promote and encourage the development and adoption of GSR or other Green Super Crops. The Chinese Government has endorsed the will for developing agricultural systems to be “resource saving and environment friendly” by 2020. However, the progress has been limited so far in societal construction and public awareness, despite the tremendous achievements in plant science research and varietal development of GSR.

3.5 Further expansion of breeding goals

With the increase of knowledge and the development stages of human society, the view of human society on the roles of food for human being is evolving. Therefore the breeding goals for food crops including the major cereals also have to evolve accordingly to address the further needs by both the consumers and producers.

From consumers’ standpoint, crop products need to be more nutritious to improve consumers’ health, in addition to providing calories. For example, the international Harvest Plus project took iron, vitamin A and zinc as targets of improvement to address the need for micronutrients by the consumers, especially those in developing countries[15]. Other phyto-nutrients such as antioxidants[16] and resistant starch[17] have also been regarded as having beneficial effects on human health. Plant science research and breeding need to address the issue of human health by enhancing such beneficial phyto-nutrients, a goal referred to as biofortification.

Labor saving, mechanization and less intensive field management in crop production are now emerging as deemed necessary with the rapid urbanization in new economies like China. In rice, for example, such changes require the crop varieties to have traits for facilitating direct seeding and machine transplantation and harvest; it may also be desirable for the crop to have herbicide-tolerance and reduced grain water content at maturity to reduce labors in field management and grain drying. This together with the green traits, which aim to decrease fertilizer and pesticide consumption and water use, can greatly reduce the cost for the production, thus providing huge benefit to the farmers.

4 Crop breeding in the post genomics era

4. 1 Genomic research

The databases now are full of genome sequences and other genomic information. High quality genome sequences have been available for major crops including rice and maize, and draft sequences have been produced for many other crops. Large numbers of accessions have been re-sequenced providing the basis for a range of studies and development, including genome-wide association study (GWAS) and allele mining.

There have also been huge advances in functional genomic research in crops, aiming to characterize the functions of the genomes. In rice, for example, the functional genomics project has developed technological and resource platforms for high throughput characterization of gene functions including:large collections of mutant libraries generated by T-DNA and transposon insertions as well as chemical and physical inductions, transcriptomes of various tissues from numerous genotypes, full length c-DNAs of both indica and japonica rice, metabolomes of diverse germplasms, and genome sequences for thousands of accessions of both wild and cultivated rice. Such developments have enabled the rapid progress in isolation and characterization of rice genes. Hundreds of genes have been isolated and functionally characterized in the last decades with accelerated pace in recent years[18-19].

4.2 Genomic breeding

The development in genomic research has provided unprecedented opportunities for genomic breeding to become reality. The notion of genomic breeding may be viewed as composed of two major parts:genome design, and genome engineering, both of which will take long and gradual processes to evolve.

1) Genome design. Zhang et al[18] outlined, with modification here, the concept of genome-based varietal design, which comprises four different levels:(1)the yield limit that can be achieved through a population structure that can make maximum use of the solar energy under a given ecological condition; (2)the plant architecture to realize the population structure; (3)the traits to construct the plant architecture and to achieve high quality, high nutrient-use efficiency, resistances to multiple biotic and abiotic stresses, and other traits according to diverse breeding goals; and (4)the genes and regulatory network to produce the traits. Clearly the ability of such varietal design is critically dependent on the understanding of the genes and the regulatory network of the genome, and also the development in a range of technology.

2)Genomic engineering. The breeding process is similar to engineering in many ways. At present level of development and understanding, genomic engineering may involve the following classes of technologies including:(1)genomic prediction;(2)genomic selection;(3)gene editing; and (4)transgenics.

①Genomic prediction. Depending on the targets of selection in the breeding program, genomic prediction may vary in complexity. For simple cases of improving simple traits involving single genes such as major genes controlling disease resistances, the results are usually highly predictable without the need for complex prediction technology. For complex traits like yield and heterosis, prediction technology deems needed not only for improving the efficiency of selection, but also ultimately essential for genome design. Progress has been made in recent years in statistical prediction of the trait performance making use of phenotypes from field experiments, and genotypes of the whole genome from re-sequencing[20]. Data from other-omes such as transcriptomes, proteomes, metabolomes may also be useful for predicting the performance. Analysis of the relationship of the multi-omes with agronomic performance may eventually lead to the development of crop versions of systems biology, which may further help predicting and designing.

②Genomic selection. Genomic selection is a natural extension of marker-assisted selection. Based on development of technologies for high throughput detection of DNA polymorphisms and making maximum use of information about genetics, functions and phenotypic effects of the genes, genomic selection aims at simultaneously selecting for the targets (genes and traits), non-targets, and the entire genome backgrounds, according to the goals of breeding programs.

Two key technologies are needed to perform precise genomic selection, (1)cost-effective genotyping of the whole genome, and (2)a gene-specific selection system for each gene. Microarrays based on large genome re-sequencing have been designed and used in breeding programs in several crop species[21-22], which can precisely determine the genotypes of the parental origin for thousands of SNPs distributed in the entire genome and identify the recombination breakpoints in the progeny plants. A gene-specific selection system consists of two parts: forward selection for the target gene, which is usually a functional marker within the gene, and backward selection for recombinations using closely linked markers bracketing the target gene. These two technologies together could provide a powerful tool for precise introgression of genes into the genetic backgrounds of elite varieties with well defined genomic segments without linkage drag, thus producing isogenic lines, or desired variant forms. This may be particularly useful for deploying disease resistance genes by the multiline strategy, which may provide an effective means for durable resistance.

③Gene editing. Concurrently, there have been rapid developments in recent years in gene editing technology, such ZFNs, TALENs and CRISPR/Cas9[23]. It has now become a reality to modify the DNA sequence of any gene, especially to create loss-of-function mutations. Since many desired traits are controlled by recessive genes in crop plants as elucidated by functional genomic research, such modifications hold great promise in varietal improvement. Future development in the technology may make it possible to modify the sequence with less restriction, so that the gene sequence can be modified in both ways, either loss of function or gain of function. This may lead to new paradigm in plant breeding.

④Transgenics. Research, development and large-scale adoption of transgenic crops have produced huge impacts in plant breeding, seed industry and crop production. In future breeding, transgenic technology may have an indispensible role at least in the following respects: (1) for traits that do not exist in the crop, like the case of introducing genes from *Bacillus* to crops for insect resistance, which has generated tremendous economical and environmental benefits; (2)for traits involving pathways each regulated by multiple genes, like in the case of provitamin A which has great potential for improving the nutritional status for a large segment of the world population; and (3)for simultaneous improvement of multiple traits with one transgenic event, by producing constructs harboring multiple genes, like the case of SmartStax[24] with multiple resistances to insects and broad spectrum tolerance to herbicides.

4.3 Integration of the technologies and seed industry

The ability for constructing the technological platforms and utilization of the technologies critically depends on the capacity of the seed industry. Although each of the single technologies may individually contribute to the plant breeding programs to certain extent, integration of these technologies into breeding programs together with field breeding would make the technologies really powerful and deliver. However such integration would require large investment in infrastructure, facilities, human resources and also team work, which means the operation model of large seed companies rather than small mills. Seed industry is in general quite weak in almost all the developing countries, although there has been tremendous progress in plant science research in countries like China.

In China, there is a trend supported by the government to enhance the seed industry by encouraging the seed companies to develop research capacity to set up their own breeding programs and to make use of the latest developments of genomic research and biotechnology in breeding activities. Clearly, there is a long way to go in order for such development to reach an industrial scale, and to make impact on crop production.

5 Perspective

With the increased population, elevated living standard, and intensified resource and environment pressure, breeding goals will also evolve dynamically to address the needs of human societies for calories, nutrition, environmental sustainability, and other demands. Plant breeding should also take into account of the benefits of the producers including the small household farmers for the need of improving efficiency in crop production by diversifying field management practice to reduce the labor and cost, and also for mechanization. With the advance in plant science research and genomic technology, crop breeding is becoming increasingly more based on broad, sound and cutting edge sciences. Development in science and technology will also enable more efficient exploitation of the diverse germplasms including those of distantly related species, much of which has been presently untapped. Information technology, bioinformatics and systems biology will also have important roles in future plant breeding. And last but not the least, the trend of globalization and commercialization of breeding activities is irreversible and will continue to serve as an engine for the development of seed industry and breeding technology.

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