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Development of High Yielding Rice Varieties for Favorable Ecosystem with 40% Higher Yield than the Present Variety: A Review Paper

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Abstract: In 1966, IR8, the first semi-dwarf, high yielding modern rice variety was released for the tropical irrigated lowland; it creates a green revolution in this period in rice production. Much effort has been given in increasing the rice yield to feed the ever increasing population of the world in general and Bangladesh in particular. Now the yield of modern high yielding varieties has reached to a plateau. Increasing the yield potential of rice is one of the frontier projects of breeding rice. Therefore, the paper reviewed to disseminate information about the development of high yielding rice varieties for favorable ecosystem with 40% higher yield than the present variety. The new plant type is one of the ideas to increase rice yield described by IRRI scientist. New plant type has low tillering capacity, few unproductive tillers, 200-250 grains per panicle, 90-100 cm plant height, thick and sturdy stems, thick, dark green and erect leaves, vigorous root system, 100-130 days growth duration and increased harvest index. Tailoring rice plant architecture is also a hypothesis to increase the rice yield. Scientists have discovered a wonder rice gene that could dramatically increase yields of one of the world's most important food crops. Preliminary tests show that yields of modern long-grain "indica" rice varieties, the world's most widely grown types of rice, can rise by 13-36% when infused with the so-called SPIKE gene. Improvement in the photosynthetic efficiency has played only a minor role in the remarkable increase in productivity achieved; further increase in the yield potential will rely in large part on improved photosynthesis. Critical examination of the inefficiencies in photosynthetic energy transduction in crops from light interception to carbohydrate synthesis, classical breeding, systems biology and synthetic biology are providing new avenues for developing more productive germplasm.

Key words: Rice · New plant type · Super rice · Ideotype · Spike gene · Yield

INTRODUCTION

Rice is the staple food of about 160 million people of Bangladesh. It provides nearly 48% of rural employment, about two-third of total calorie supply and about one-half of the total protein intakes of an average person in the country. Rice sector contributes one-half of the agricultural GDP and one-sixth of the national income in Bangladesh. Almost all of the 13 million farm families of the country grow rice. Rice is grown on about 10.5 million hectares which has remained almost stable over the past three decades. About 75% of the total cropped area and over 80% of the total irrigated area is planted to rice. Thus, rice plays a vital role in the livelihood of the people of Bangladesh.

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Total rice production in Bangladesh was about 10.59 million tons in the year 1971 when the country's population was only about 70.88 millions. However, the country is now producing about 25.0 million tons to feed her 135 million people. This indicates that the growth of rice production was much faster than the growth of population. This increased rice production has been possible largely due to the adoption of modern rice varieties on around 66% of the rice land which contributes to about 73% of the country's total rice production. However, there is no reason to be complacent. The population of Bangladesh is still growing by two million every year and may increase by another 30 millions over the next 20 years. Thus, Bangladesh will require about 27.26 million tons of rice for the year 2020. During this time total rice area will also shrink to 10.28 million hectares. Rice yield therefore, needs to be increased from the present 2.74 to 3.74 t/ha. Most of this increase has to come from greater yields on existing cropland to avoid environmental degradation, destruction of natural ecosystems and loss of biodiversity [1, 2]. Irrigated boro rice land contributes major part of rice production. Rice varieties with higher yield potential must be developed to enhance the average farm yields of irrigated rice.

Yield potential is defined as the yield of a variety when grown in environments to which it is adapted with nutrients and water non-limiting and with pests, diseases, weeds, lodging and other stresses effectively. Yield potential of irrigated rice has experienced two quantum leaps. The first one was brought by the development of semi-dwarf varieties in late 50s in China and early 60s at the International Rice Research Institute (IRRI). Dwarf breeding was initiated in China in 1956 using the Sd-1 gene from Ai-zi-zhan [3]. In 1959, the first dwarf variety, Guang-chang-ai, was developed in China. In 1962, plant breeders at IRRI made crosses to introduce dwarfing genes from Taiwanese varieties such as Dee-geo-woo-gen, Taichung Native 1 and Igeo- tse to tropical tall land races. In 1966, IR8, the first semi-dwarf, high yielding modern rice variety, was released for the tropical irrigated lowlands [4]. The birth of IR8 increased yield potential of irrigated rice crop from 6 to 10 t/ha in the tropics [5]. The second one was brought by the development of hybrid rice in 1976 in China [6]. Standard heterosis of indica/indica hybrids was reported to range from 15 to 25% in China, but no information is available about the actual increase in yield potential by the hybrid rice in temperate and subtropical areas. In the tropics, Peng *et al*. [7] reported that indica/indica hybrid rice has increased yield potential by 9% compared with the best inbred cultivars in irrigated lowlands. Improving rice yield potential has been the main breeding objective in many countries for many years. However, stagnant yield potential of semi-dwarf indica inbred rice varieties was observed in the tropics since the release of IR8 [7], although genetic gain in yield per day has been achieved due to reduction in total growth duration. Therefore, it would give trust on development of high yield potential varieties with higher yield per day.

IRRI’s New Plant Type Breeding: Donald [8] proposed the ideotype approach to plant breeding in contrast to the empirical breeding approach of defect elimination and selection for yield per se. He defined "crop ideotype" as an idealized plant type with a specific combination of characteristics favorable for photosynthesis, growth and grain production based on the knowledge of plant and crop physiology and morphology. Simulation models predicted that a 25% increase in yield potential was possible by modification of the following traits of the current plant [9]: (1) enhanced leaf growth combined with reduced tillering during early vegetative growth, (2) reduced leaf growth and greater foliar N concentration during late vegetative and reproductive growth, (3) a steeper slope of the vertical N concentration gradient in the leaf canopy with a greater proportion of total leaf N in the upper leaves, (4) increased carbohydrate storage capacity in stems and (5) a greater reproductive sink capacity and an extended grain-filling period. These traits are both physiological and morphological.

To break the yield potential barrier, IRRI scientists proposed modifications to the high-yielding *indica* plant type in the late 1980s and early 1990s [10]. The newly designed plant type was mainly based on the results of the simulation modeling and new traits were mostly morphological since they are relatively easy to select compared with physiological traits in the breeding program. The proposed new plant type (NPT) (Fig. 1) has low tillering capacity (3 to 4 tillers when direct seeded), few unproductive tillers, 200 to 250 grains per panicle, a plant height of 90 to 100 cm, thick and sturdy stems, leaves that were thick, dark green and erect, a vigorous root system, 100 to 130 days growth duration and increased harvest index [7].

Fig. 1: Suggested ideotype changes for continued improvement of rice yield. (a) Traditional plant type; (b) Semi dwarf plant type (Present varieties); (c) New plant type.

Breeding work began in 1989 at IRRI when about 2,000 entries from the IRRI germplasm bank were grown during the dry (DS) and wet (WS) seasons to identify donors for the desired traits [10]. Donors for low tillering trait, large panicles, thick stems, vigorous root system and short stature were identified in the "bulu" or javanica germplasm mainly from Indonesia. This germplasm is now referred to as tropical japonicas [10]. The first-generation NPT lines based on tropical japonicas were developed in less than 5 years. They were grown in a replicated observational trial for the first time in late 1993.

As intended, the NPT lines had large panicles, few unproductive tillers and lodging resistance. Grain yield was disappointing, however, because of low biomass production and poor grain filling. The poor grain filling of NPT lines was probably due to lack of apical dominance within a panicle [11], compact arrangement of spikelets on the panicle [4].

In 1995, development of second-generation NPT lines was initiated by crossing first-generation tropical japonica NPT lines with elite indica parents. Multiple site-year comparisons of first-generation NPT lines with highest yielding indica varieties have shown that the original NPT design did not have sufficient tillering capacity. Thhuugh first-generation NPT lines using tropical japonica did not produce rice varieties but that reached the expected yield performance. The introduction of indica genes to a tropical japonica background to develop intermediate-type varieties between indica and japonica has resulted in several promising second-generation NPT lines.

Goals were to increase tillering capacity to improve biomass production and compensation when tillers were lost to insect damage or other causes during the vegetative stage. In the 2002 DS, four second-generation NPT lines produced significantly higher yield than the check variety, IR72.

"Super" Rice in China: Huang [3] developed bushy-type varieties with early vigor in 1980s. These varieties are tolerant of shading and high plant density and were widely grown in southern China. Yang *et al*. [12] stated that a further increase in rice yield potential has to come from a combination of improvement in plant type and use of growth vigor. They proposed an erect panicle plant type and developed Shennong265 with this trait, which was grown in Liaoning Province. Developed three-line inter subspecific F1 hybrid rice between indica and japonica with a heavy-panicle plant type, which is suitable for rice-growing areas such as Sichuan with high humidity, high temperature and limited solar radiation. Although progress has been achieved in increasing rice grain yield through crop improvement, China's rice breeding activities for increasing yield potential using an ideotype approach were not organized at the national level until 1996.

Stimulated by IRRI's NPT breeding program, China established a nationwide mega project on the development of ''super'' rice in 1996 [13], with the following objectives:

- To develop ''super'' rice varieties with a maximum yield of 9-10.5 t/ha by 2000, 12 t/ha by 2005 and 13.5 t/ha by 2015 measured from a large planting area of at least 6.7 ha.
- To develop ''super'' rice varieties with yield potential of 12 t/ha by 2000, 13.5 t/ha by 2005 and 15 t/ha by 2015. These yields will be achieved in experimental and demonstration plots.
- To raise the national average rice yield to 6.9 t/ha by 2010 and to 7.5 t/ha by 2030 by developing ''super'' rice varieties.

The ''super'' rice varieties can be developed by breeding inbred and/or hybrid varieties. A ''super'' hybrid rice breeding program was started in 1998 by Prof. Longping Yuan. In this program, the strategy was to combine an ideotype approach with the use of intersubspecific heterosis [14]. The ideotype was reflected in the following morphological traits:

1. Moderate tillering capacity (270–300 panicles m^{-2}).
2. Heavy (5 g per panicle) and drooping panicles at maturity.
3. Plant height of at least 100 cm (from soil surface to unbent plant tip) and panicle height of 60 cm (from soil surface to the top of panicles with panicles in natural position) at maturity.
4. Top three leaves:
    - Flag-leaf length of 50 and 55 cm for the 2nd and 3rd leaves. All three leaves are above panicle height.
    - Should remain erect until maturity. Leaf angles of the flag, 2nd and 3rd leaves are around 58, 108 and 208, respectively.
    - Narrow and V-shape leaves (2 cm leaf width when flattened). Thick leaves (specific leaf weight of top three leaves = 55 g m^{-2}).
    - Leaf area index (LAI) of top three leaves is about 6.0.
5. Harvest index of about 0.55.

It is clear that the plant type of China's ''super'' rice has many similarities with IRRI's NPT design. Both emphasize large and heavy panicles with reduced tillering capacity and improved lodging resistance. It was expected that harvest index could be improved with increased sink size and few unproductive tillers. Other common traits are erect-leaf canopy and slightly increased plant height in order to increase biomass production. The distance between panicle height and plant height can be increased by either reducing panicle height or increasing plant height.

The initial breeding strategy for the NPT at IRRI was to use genes for large panicles and sturdy stems from tropical japonica germplasm. The second step was to cross the improved tropical japonica with elite *indica* varieties to produce an intermediate rice type. In breeding for ''super'' hybrid rice in China, the two-line or three-line method was used to develop F_1 hybrid combinations by crossing an intermediate type between *indica* and *japonica* with an *indica* parent in order to use inter sub specific heterosis. Great progress has been achieved in China's ''super'' hybrid rice breeding project by combining an ideotype approach with the use of inter sub specific heterosis.

Tailoring Rice Plant Architecture: Plant architecture is the three-dimensional organization of the part of a plant that is above ground. It encompasses the branching (tillering) pattern, plant height, arrangement of leaves and the structure of the reproductive organs. It is of major agronomic importance as it determines the adaptability of a plant to cultivation, its harvest index and potential grain yield [15]. Plant architecture, is subject to strict genetic control and grain production in cereal crops is governed by an array of agronomic traits. Recently, significant progress has been made in isolating and collecting rice mutants that exhibit altered plant architecture. The improved high-yield variety has normal top functional leaves and the super high-yield variety has desired leaf shape and small leaf angle. The panicles are droopy and lower than the top three leaves and the top three functional leaves are erect, longer and slightly rolled [12]. The architecture of a plant depends on the nature and relative arrangement of each of its parts; it reflects, at any given time, the expression of equilibrium between endogenous growth processes and exogenous constraints exerted by the environment. The aim of architectural analysis is, by means of observation and sometimes experimentation, to identify and understand these endogenous processes and to separate them from the plasticity of their expression resulting from external influences. The endogenous regulatory principles that control plant architecture were documented [16].

These authors proposed that plant architecture is species specific, indicating that it is under strict genetic control, although it is also influenced by environmental conditions such as light, temperature, humidity and nutrient status.

In addition, the basis of leaf architecture and the role of cell division and cell growth in morphogenesis influence plant architecture. Nowadays, it is becoming widely accepted that plant growth models may provide efficient tools to study plant growth behavior [17, 18], since they can not only complement field experiments, but also save time and resources. Therefore, researchers dedicated themselves to studying ideotype breeding based on plant models [19, 20]. Even though Cilas *et al*. [20] investigated ideotype breeding from the architectural point of view and Yin *et al*. [19] from the physiological point of view using a process-based plant growth model, they agree that critical relationships exist between plant architectures and physiological processes during plant growth. This view is also held by researchers like [18, 21, 22, 23, 24]. The design of ideotypes should thus take both architectural and physiological aspects into account. In parallel, functional–structural plant growth models were developed [23, 25], combining the description of organogenesis (plant development), photosynthesis and biomass partitioning. They offer interesting perspectives to improve plant breeding. Janoria [26] has suggested an alternative ideotype of rice that has been developed to maximize utilization of the available horizontal space (the arable earth surface) and the resources from the vertical space *viz.* carbon dioxide, oxygen, solar radiation, water and solubilized mineral nutrients to give the highest possible yields in any given situation (Fig. 2). He assumed that the most efficient plant type would be the one that occupies a minimum of horizontal but maximum of vertical space. On these premises, he identified morphological traits as the most likely to promote maximum utilization of the space. The characteristic features of the novel ideotype include taller stature; fewer, tough, non-lodging and all effective culms; upright growth habit; fewer, well spaced, thick, large but stiff leaves able to maintain erect position; heavy panicles with limited intra plant variation for panicle yield, high light transmission ratio and a deep, extensive root system. Janoria emphasized that the semi tall plant type would require closer spacing.

Sharma *et al*. [27] studied variation for grain yield and its components in closely related rice genotypes representing an ideotype designed to maximize space utilization. He concluded that a semi-tall plant type necessitates planting at closer spacing.

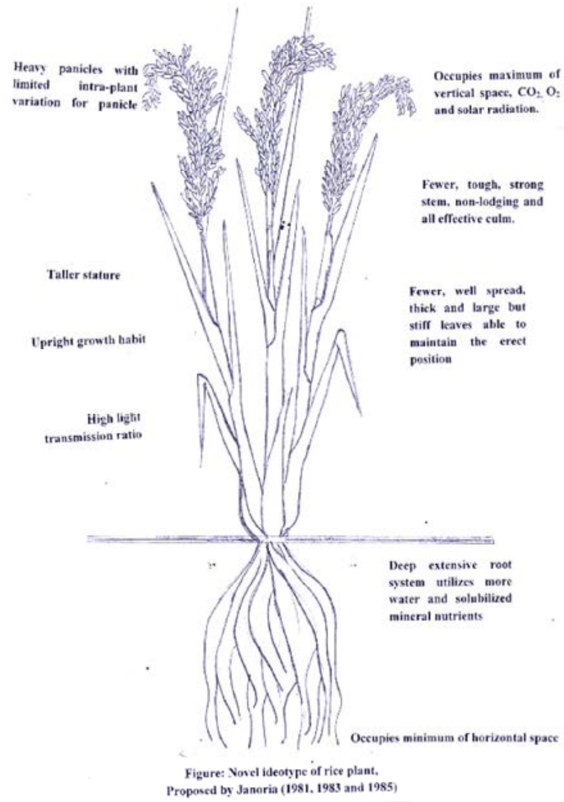

Fig. 2: Novel ideotype of rice proposed by Janoria [26].

He also suggested that reduction in tiller number per plant would lead to higher grain yield per plant and optimum plant height at closer spacing seems to be slightly higher than the present 108 cm. Existing genotypes conforming to the semi-tall ideotype comprise substantial variation for all important ideotype attributes and selective intercrossing could lead to superior second generation genotypes. Sharma *et al*. [27] studied rice ideotype designs towards space geometry in relation to environments. They proposed rice ideotype models for closer spacing and normal spacing. A promising new plant type breeding line, NPT57K-70-22, developed at JNAU appeared to be resistant to case worm at Raipur, Chhattisgarh, India. It has a much higher grain number per panicle, lower panicle number and greater plant height than semi dwarf varieties. Studies were undertaken during the 1998 and 1999 wet sea-sons to confirm the observed high resistance of JR57K-70-22 and to evaluate two more promising NPT breeding lines along with IR36 and Mahamaya, recommended cultivars in Chhattisgarh [28]. This study confirmed that inspite of good yielding ability NPT line have the high resistance to case-worm insect.

Wonder Rice Gene: Scientists have discovered a wonder rice gene that could dramatically increase yields of one of the world's most important food crops. Preliminary tests show that yields of modern long-grain "indica" rice varieties, the world's most widely grown types of rice, can rise by 13-36% when infused with the so-called SPIKE gene. They showed that SPIKE is indeed one of the major genes responsible for the yield increase that breeders have spent so many years searching for. Testing of new rice varieties infused with the gene is under way across several developing countries in Asia, said rice breeder Tsutomu Ishimaru, head of the IRRI-led SPIKE breeding programme. They believed that these will contribute to food security in these areas once the new varieties are released," Ishimaru said. Increasing the yield means growing more rice on the same amount of land, using the same resources. But there is no definite timetable for when the rice containing the SPIKE gene will be distributed to farmers, according to IRRI spokeswoman Gladys Ebron. The SPIKE gene was first discovered by Japanese breeder, Nobuya Kobayashi, following long-running research starting in 1989 on a tropical "*japonica*" rice variety that is grown in Indonesia, Ebron told AFP. Tropical *japonica* rice is mainly grown in East Asia and accounts for just 10% of global rice production. Breeders from IRRI, a non-profit research group established in the 1960s, then worked to incorporate the gene into "*indica"* varieties that are widely used in major rice-growing areas of Asia. Ebron said the transfer did not involve genetical modification of the crop, a controversial issue in food production. She reported that it's just conventional breeding.

Physiological Interventions for Higher Yields: Improving crop yield to meet the demands of an increasing world population for food and fuel is a central challenge for plant biology. This goal must be achieved in a sustainable manner (that is, with minimal agricultural inputs and environmental impacts) in the face of elevated levels of CO_2 and more extreme conditions of water availability and temperature. Agricultural yields have generally kept pace with demand in the recent past as a result of the gains made through breeding programs and farming practice, but crop yields are now reaching a plateau. One fundamental component of plant productivity that has not been used to select for increased yield is photosynthesis. There is now an opportunity to exploit our extensive knowledge of this fundamental process for the benefit of humankind.

Increase in the yield potential of the major food crops has contributed considerably to the rising food demand/ supply over the past decades. Improvement in the photosynthetic efficiency has played only a minor role in the remarkable increase in productivity achieved; further increase in the yield potential will rely in large part on improved photosynthesis. Critical examination of the inefficiencies in photosynthetic energy transduction in crops from light interception to carbohydrate synthesis, classical breeding, systems biology and synthetic biology are providing new avenues for developing more productive germplasm. Opportunities which could be exploited in near future includes improving the display of leaves in crop canopies to avoid light saturation of individual leaves and further investigation of the photo-respiratory bypass that has already improved the productivity of modern cultivars.

Source and Sink: Growth and development of plants are dependent upon the availability of assimilates and their utilization in the sink tissues. Based on their ability to produce or consume assimilates, plant organs can be divided into two kinds: (1) Photosynthetically active source organs defined as net exporters of photo-assimilates and (2) Sink organs defined as net importers of fixed carbon. Sink tissues are either utilization sinks such as meristem or roots where most of the imported assimilates are used for growth and only small amounts are stored temporarily, or storage sinks like tuber and seeds, where the imported metabolites are deposited in the form of storage compounds such as sucrose, starch, protein or fatty acids [29]. There is, however, a transition from sink to source in some organs during plant development. A leaf during initial stages of its development acts as sink and becomes a source as it starts exporting assimilates. Most discussions of the whole plant factors limiting crop yield focuses on whether the source or the sink is the limiting factor [30]. Clearly, as is evident from Fig. 3, it is incorrect to consider the source and sink as operating independently. Indeed, it is suggested that the concepts of source and sink are redundant terms in the context of considering regulation and limitation of the biochemical processes that determine crop yield. Not only do regulation mechanisms ensure that all parts are balanced, but there is control during development. For example, seed number, an important yield component and an index of sink strength, is determined by net photosynthesis during the reproductive phase [30]. More fundamentally, source

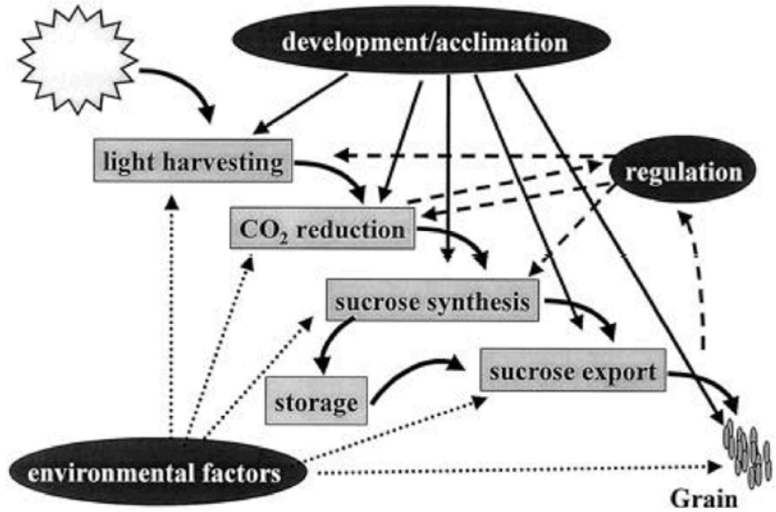

Fig. 3: Photosynthesis—from light harvesting to grain production.Flow diagram indicates the principal subsystems that connect to convert sunlight into crop yield. The influence of internal regulatory mechanisms (dashed lines), environmental factors (dotted lines) and development/acclimation alter both the rate and capacity of the material and energy flux through the whole system.

and sink are rather arbitrary divisions in a continuous process of linked biochemical reactions (Fig. 2); as with any such pathway, limitation is distributed along this continuum and discussion of 'source and sink limitation' is as flawed as the consideration of 'rate limiting steps' in biochemistry. For rice, there is clearly great promise in manipulation of the pathways leading to starch deposition in the developing grain, or in increasing the transport capacity of sucrose through to the developing spikelet [31].

Grain yield of major cereals including rice, wheat, barley and sorghum is largely determined by the source-sink relationship in which florets are the primary photosynthate sink while the top three leaves on a stem (the flag leaf, flag-1 and flag-2), particularly the flag leaf, are the primary source. In rice, over 80% of the carbohydrates accumulated in grains are produced by the top two leaves. The source and sink capacities in cereals are phenotypically associated with some morphological traits such as size and shape (or type) of the source leaves, panicles and kernels. In cereal breeding efforts for high yield potential, selection for yield per se or on yield components in early segregating generations has not been effective because of low heritability of yield in the former case and the negative correlation between yield components of latter, which is also known as the concept 'yield component compensation' arising either from the developmental allometry or physiological competition. Reproductive stages of development, from initiation of floral development to anthesis, are pivotal in determining yield potential and especially the rapid spike-growth phase which has duration of 25 days in irrigated spring wheat in northwest Mexico and Argentina. During this period, final grain number is determined; a major factor determining subsequent partitioning of assimilates to yield, as well as heavily influencing the assimilation rate of the photosynthetic apparatus during grain filling. Duration of spike growth relative to other phenological stages shows genetic variation. This is associated with sensitivities to photoperiod, vernalization and developmental rate independent of these stimuli (earliness *per se*). Fischer [32, 33] established the critical nature of the rapid spike-growth phase in determining yield. Based on this, it has been suggested that the possibility exists of improving final grain number and yield potential by manipulating genes associated with sensitivity to photoperiod (*Ppd*) and vernalization (*Vrn*), as well as earliness. The hypothesis is based on the idea that by increasing the partitioning of assimilates to spike growth and therefore spike biomass, potential floret survival will be increased and hence yield potential raised [34]. Experiments in which different radiation regimes were compared during this critical phase are consistent with the hypothesis [33, 35]. Recently, the duration of rapid spike growth has been successfully manipulated using photoperiod, revealing a strong relationship between its duration and the number of fertile florets/spike. By maintaining plants at a relatively short photoperiod during this growth phase, the number of days from terminal spikelet to heading was increased from 50 to 70 days, with 13 and 9 h photoperiods, respectively, while the number of fertile florets per spike increased from 77 to 108.

From a practical point of view, breeders have tried to modify sink capacity of wheat by modifying spike morphology. A good example of this approach was reported by Dencic [36] who crossed genotypes with branched tetrastichon (two spikelets per node of rachis) with high-yielding lines that contained other desirable traits such as high yield, disease resistance and quality. Single, back and top cross progenies were derived and desirable lines selected using a pedigree breeding approach. After 10 years of breeding and selection, 229 lines with desirable characteristics were yield tested, of which four lines yielded better (13%) than the standards (Jugoslavija and Skopljanka). The following morphological traits were improved over the standards: Spike length (16%), spikelets per spike (10%), grains per spikelet (9%) and grains per square meter (18%). The yield advantage was achieved in spite of the fact that tetrastichon donor lines had problems of empty florets or shriveled grain with very low kernel weight.

Nitrogen Use Efficiency: Nitrogen is the indispensable nutrient to rice production and its uptake is affected by a variety of characteristics, fertilizer application, soil conditions and environmental factors. Rational application technique and nitrogen use efficiency for rice in the field had been studied by many scholars, which had a direct effect on high-yield and high-efficiency production of rice [12, 37, 38, 39, 40].

Yield of rice in sandy and clay soil was increased by nitrogen application and that in clay soil was higher than that in sandy soil, but the effect of nitrogen on yield increment was greater in sandy soil than in clay soil. Nitrogen harvest index and physiological Nitrogen use efficiency were higher in sandy soil than in clay soil. Apparent nitrogen recovery efficiency, partial factor productivity for applied nitrogen and soil nitrogen dependent rate were higher in clay soil than in sandy soil. Agronomic nitrogen use efficiency was varied in different cultivars under different soil conditions. N harvest index, agronomic N use efficiency, physiological N use efficiency, partial factor productivity for applied N and soil N dependent rate were decreased significantly with the increment of the amount of nitrogen applied under two soil conditions [41]. Adjusting the proportion of N application at different growth stages may reform the source–sink contradiction of yield, thus further increasing rice yield [42].

Photosynthesis Efficiency: Scientists at the University of Arkansas System Division of Agriculture have found that they can harness photosynthesis – the process that plants use to convert light energy to chemical energy – to increase rice yields by up to 30%. A research group led by Andy Pereira of the Crop, Soil and Environmental Sciences Department faculty examined a protein that acts as a "switch" to activate genes that can enhance the photosynthesis activity of rice plants. The researchers discovered that the protein, known as higher yield rice (HYR), could enable the plants to survive stress, thrive and increase productivity. The results of the research are published in *Nature Communications*, an online multidisciplinary journal of the natural sciences (University of Arkansas News, 2015).

Phytohormone: The research team, led by the Durham Centre for Crop Improvement Technology and including experts at the University of Nottingham, Rothamsted Research and the University of Warwick, has discovered that plants have the natural ability to regulate their growth independently of Gibberellin, particularly during times of environmental stress. They found that plants produce a modifier protein, called SUMO that interacts with the growth repressing proteins. The researchers believe that by modifying the interaction between the modifier protein and the repressor proteins they can remove the brakes from plant growth, leading to higher yields, even when plants are experiencing stress [43]. The interaction between the proteins can be modified in a number of ways, including by conventional plant breeding methods and by biotechnology techniques. The research was carried out on Thale Cress, a model for plant research that occurs naturally throughout most of Europe and Central Asia, but the scientists say the mechanism they have found also exists in crops such as barley, corn, rice and wheat.

CONCLUSION

Rice scientists increased rice varietal yields during the 1950s and 1960s by improving the plant type and since the 1970s by exploiting the phenomenon of heterosis in developing F_1 hybrid cultivars. Both approaches seem to have reached a plateau, with yields of 8 to 9 t/ha. If still higher yields are to be achieved, total biomass yield has to be increased while maintaining a reasonable grain: Straw ratio. Research efforts should aim at: (1) Increasing leaf area; (2) Increasing photosynthetic efficiency per unit leaf area and (3) Improving fertilizer responsiveness and lodging resistance. This would require combining ideal plant morphology with favorable vigor; *indica-japonica* hybridization should meet this objective. High stomata frequency of *indicas* could be combined with *japonica* traits of compact plant type, higher specific leaf weight, higher chlorophyll content per unit leaf area and higher nitrogen and RuBPC (Ribulose bisphosphate carboxylase) content. All these characteristics are advantageous to close planting and to increasing photosynthetic efficiency of leaves and total biomass yield. *Indica-japonica* crosses can be used to achieve ideal plant morphology and increased growth vigor.

REFERENCES

1. Cassman, K.G., 1999. Ecological intensification of cereal production systems: yield potential, soil quality and precision agriculture. Proc. Natl. Acad. Sci. U.S.A. 96: 5952-5959.
2. Tilman, D., K.G. Cassman, P.A. Matson, R. Naylor and S. Polasky, 2002. Agricultural sustainability and intensive production practices. Nature, 418: 671-677.
3. Huang, Y., 2001. Rice ideotype breeding of Guangdong Academy of Agricultural Sciences in retrospect. Guangdong Agric. Sci. 3: 2-6 (in Chinese).
4. Khush, G.S., W.R. Coffman and H.M. Beachell, 2001. The history of rice breeding: IRRI's contribution. In: Rockwood, W.G. (Ed.), Rice Research and Production in the 21st Century: Symposium Honoring Robert F. Chandler, Jr., International Rice Research Institute, Los Ban˜os, Philippines, pp: 117-135.
5. Chandler Jr R.F., 1982. An Adventure in Applied Science: A History of the International Rice Research Institute. International Rice Research Institute, Los Ban˜os, Philippines, pp: 233.
6. Yuan, L., Z. Yang and J. Yang, 1994. Hybrid rice in China. In: Virmani, S.S. (Ed.), Hybrid Rice Technology: New Developments and Future Prospects. International Rice Research Institute, Los Ban˜os, Philippines, pp: 143-147.
7. Peng, S. and G.S. Khush, 2003. Four decades of breeding for varietal improvement of irrigated lowland rice in the International Rice Research Institute. Plant Prod. Sci., 6: 157-164.
8. Donald, C.Z., 1968. The breeding of crop ideotypes. Euphytica 17, 385-403. Evans, L.T., 1993. Crop Evolution. In: Adaptation and Yield, Cambridge University Press, Cambridge, UK, pp: 498.
9. Dingkuhn, M., F.W.T. Penning de Vries, S.K. De Datta and H.H. Van Laar, 1991. Concepts for a new plant type for direct seeded flooded tropical rice. In: Direct Seeded Flooded Rice in the Tropics, International Rice Research Institute, Los Ban˜os, Philippines, pp: 17-38.
10. Khush, G.S., 1995. Breaking the yield frontier of rice. Geo Journal, 35: 329-332.
11. Yamagishi, T., S. Peng, K.G. Cassman and R. Ishii, 1996. Studies on grain filling characteristics in ''New Plant Type'' rice lines developed in IRRI. Jpn. J. Crop Sci., 65 (Extra issue No. 2): 169-170.
12. Yang, X.C. and C.M. Hwa, 2008. Genetic modification of plant architecture and variety improvement in rice. Heredity, 101: 396-404.
13. Cheng, S., X. Liao and S. Min, 1998. China's ''super'' rice research: background, goals and issues. China Rice, 1: 3-5 (in Chinese).
14. Yuan, L., 2001. Breeding of super hybrid rice. In: Peng, S., Hardy, B. (Eds.), Rice Research for Food Security and Poverty Alleviation. International Rice Research Institute, Los Ban˜os, Philippines, pp: 143-149.
15. Reinhardt, D. and C. Kuhlemeier, 2002. Plant architecture. EMBO Reports, 9: 846-851.
16. Barthélémy, D. and Y. Caraglio, 2007. Plant architecture: a dynamic, multilevel and comprehensive approach to plant form, structure and ontogeny. Ann. Bot., 99: 375-407.
17. Tardieu, F., 2003. Virtual plants: modelling as a tool for the genomics of tolerance to water deficit. Trends Plant Sci., 8: 9-14.
18. Letort, V., P.H. Cournède, A. Mathieu, P. de Reffye and T. Constant, 2008. Parametric identification of a functional-structural tree growth model and application to beech trees (*Fagus sylvatica*). Funct. Plant Biol., 35: 951-963.
19. Yin, X., P. Stam, M.J. Kropff and A.H.C.M. Schapendonk, 2003. Crop modeling, QTL mapping and their complementary role in plant breeding. Agron. J., 95: 90-98.
20. Cilas, C., A. Bar-Hen, C. Montagnon and C. Godin, 2006. Definition of architectural ideotypes for good yield capacity in Coffea canephora. Ann. Bot., 97: 405-411.

21. Rasmusson, D.C., 1987. An evaluation of ideotype breeding. Crop Sci., 27: 1140-1146.
22. Kaitaniemi, P., J.S. Hanan and P.M. Room, 2000. Virtual sorghum: visualisation of partitioning and morphogenesis. Comput. Electron. Agric., 28: 195-205.
23. Sievänen, R., E. Nikinmaa, P. Nygren, H. Ozier-Lafontaine, J. Perttunen and H. Hakula, 2000. Components of functional-structural tree models. Ann. For. Sci., 57: 399-412.
24. Fourcaud, T., X.P. Zhang, A. Stokes, H. Lambers and C. Korner, 2008. Plant growth modelling and applications: the increasing importance of plant architecture in growth models. Ann. Bot., 101: 1053-1063.
25. De Reffye, P., E. Heuvelink, D. Barthélémy and P.H. Cournède, 2008. Plant growth models. In: Jorgensen, S., Fath, B. (Eds.), Ecological Models, 4 of Encyclopedia of Ecology (5 volumes). Elsevier, Oxford. pp: 2824-2837.
26. Janoria, M.P., 1989. A basic plant ideotype for rice. Intl. Rice Res. Newsl., 14(3): 12-13.
27. Sharma, D., M.P. Janoria, M. Yasin and R.K. Sahu, 1998. Rice ideotype designs towards space geometry in relation to environment. In: National Symposium on Rice Research for 21st century, challenges, priorities and strategies at CRRI Cuttack. pp: 38-39.
28. Sharma, D., J. Mishra, B.S. Thakur and M.P. Janoria, 2002. Performance of new plant type prototype rice lines against caseworm (*Nymphula depunctalis Guenee*). Int. rice res. notes, 27(1): 38.
29. Ho, L.C., 1988. Metabolism and compartmentation of imported sugars in sink organs in relation to sink strength. Ann. Rev. Plant Physiol. Plant Mol. Biol., 39: 355-378.
30. Egli, D.B., 1998. Seed biology and the yield of grain. Walllingford, Oxford: CAB International.
31. Horton, P., S. Benson, A.V. Ruban, S. Jansson, U. Ganetag, J. Andersson and P. Gustafsson, 1999. Genetic manipulation of light harvesting in plants. J. Exper. Bot., 50: 5.
32. Fischer, R.A., 1975. Yield potential in dwarf spring wheat and the effect of shading. Crop Sci., 15: 607-613.
33. Fischer, R.A., 1985. Number of kernels in wheat crop and the influence of solar radiation and temperature. J. Agric. Sci., 100: 447-461.
34. Bingham, J., 1969. The physiological determinants of grain yield in cereals. Agricultural Progress, 44: 30-42.
35. Abbate, P.E., F.H. Andrade, J.P. Culot and P.S. Bindraban, 1997. Grain yield in wheat: Effects of radiation during spike growth period. Field Crop Res., 54: 245-257.
36. Dencic, S., 1994. Designing a wheat ideotype with increased sink capacity. Plant Breed. 112: 311-317.
37. Fu, Q.L., Y.X. Chen and J.Y. Yu, 2003. Study on statisfactory amount of nitrogen fertilizer applied on rice in the middle area of Zhejiang Provcince. Acta Pedologica Sinica, 40(5): 787-790. (in Chinese)
38. Zhang, H.C., X.Q. Wang, Q.G. Dai, Z.Y. Huo and K. Xu, 2003. Effects of N-application rate on yield, quality and characters of nitrogen uptake of hybrid rice variety Liangyoupeijiu. Scientia Agricultura Sinica, 36(7): 800-806. (in Chinese) Q.C. Zhang and G.H. Wang, 2002. Optimal nitrogen application for direct-seeding early rice. Chinese J Rice Sci., 16(4): 346-350 (in Chinese)
39. Dai, P.A., J. Nie, S.X. Zheng and J. Xiao, 2003. Efficiency of nutrient utilization of controlled-release nitrogen fertilizer for rice at different soil fertility levels. Chinese Journal of Soil Science, 34(2): 115-119. (in Chinese)
40. Liu, L.J., D.Z. Sang, C.L. Liu, Z.Q. Wang, J.C. Yang and Q.S. Zhu, 2003. Effects of real-time and site-specific nitrogen managements on rice yield and nitrogen use efficiency. Scientia Agricultura Sinica, 36(12): 1456-1461 (in Chinese)
41. Quanbao, Y.E., Z. Hongcheng, W. Haiyan, Z. Ying, W. Benfu, X. Ke, H. Zhongyang, D. Qigen and X. Ke, 2007. Effects of nitrogen fertilizer on nitrogen use efficiency and yield of rice under different soil conditions. Front. Agric., 1(1): 30-36.
42. Biao, S., F. Xumeng, T. Guangli, H. Xiangyu, S. Qirong and G. Shiwei, 2013. Optimizing nitrogen supply increases rice yield and nitrogen use efficiency by regulating yield formation factors. Field Crops Res., 150: 99-107.
43. Conti, L., S. Nelis, C. Zhang, A. Woodcock, R. Swarup, M. Galbiati, C. Tonelli, R. Napier, P. Hedden, M. Bennett and A. Sadanandom, 2014. Small Ubiquitin-like Modifier protein SUMO enables plants to control growth independently of the phytohormone gibberellin. Dev Cell. 28(1): 102-10.