Harnessing Photosynthesis In Tomorrow’s World: Humans, Crop Production And Poverty Alleviation

Abstract

Photosynthesis is the solar energy- dependent process on which food production for human existence ultimately depends. Each day passes with 854 million people hungry and, for that reason, the United Nations Millennium Declaration committed the world’s nations to ‘eradicate extreme poverty and hunger’. Sixty percent of the world’s population lives in Asia, where each hectare of land used for rice production currently provides food for 27 people, but by 2050 that land will have to sup- port at least 43 people. In 2007, about 250 million tonnes of carbon will be fixed in rice grains; by 2050, fixation will have to rise to about 400 mil- lion tonnes. However, the elite rice cultivars, which dominate the food supply of the millions of poor people in Asia, have approached a yield barrier and growth in production is slowing. In this paper, the role of photosynthesis in solving some of the food and environmental problems of tomorrow’s world is discussed. In particular, the possibilities and constraints associated with producing a very large increase in yield, water-use efficiency and nitrogen-use efficiency by developing a C4 rice are examined.

Introduction

Agriculture is the indispensable base of human society and the nature and productivity of agricul- ture is determined by water, climate and agricultural research. Today, 75% of the world’s 6.6 billion people live in the developing world where most of the world’s existing poverty is concentrated. Currently, a billion people live on less than a dollar a day and spend half their income on food; 854 million people are hungry and each day about 25,000 people die from hunger-related causes. The United Nations Millennium Declaration, agreed in September 2000, commits the world’s nations to ‘eradicate extreme poverty and hunger’. Modeled percentage increases in rice yields required by 2050 resulting from population increases, the combination of increases in temperature and CO2, and extreme weather events in four Asian countries industry. Seventy percent of all water withdrawn is used for irrigation and in the most populated country in the world, China, agriculture accounts for more than 80% of all water consumption. Only 29% of the earth’s surface is land (15.3 B ha) and only a little over a third of that is suitable for agri- culture (crops 1.4 B ha; grass/rangeland 3.9 B ha); the rest is ice, desert, forest (4.8 B ha) or mountains and is unsuitable for farming (Costanza et al. 1997; Noble and Dirzo 1997; de Haan et al. 1997). More simply stated, only 10% of the surface of the earth has topographical and climatic conditions suit- able for producing the food requirements of the 9 billion people expected to inhabit the planet by the year 2050. In 1950, there were about 2ha of farmland available to meet the food requirements of each person on the planet by 2050 the avail- able farmland will have fallen to 0.6ha/person; assuming forests and wetlands are to remain free of agriculture. Furthermore, each hectare of land used for rice production in Asia currently provides food for 27 people, but by 2050 that land will have to support at least 43 people.

For humans, agriculture is about providing food in a manner that is economically, socially and envi- ronmentally sustainable. For scientists, rice pro- duction has to be about converting the maximum fraction of solar energy into the maximum amount of chemical energy in grain in the shortest possible time; that conversion should be achieved using the smallest amount of land, water, and fertilizer. In his acceptance speech for the Nobel Peace Prize in 1970, Norman Borlaug warned that if the frighten- ing power of human reproduction was not curbed the success of the Green Revolution would only be ephemeral. Since that speech, world population has already increased by 75% and is continuing to increase; in the 21st century the population of Asia will rise by about 50% to 5.6 billion. A second ‘Green Revolution’ will be required to feed Asia but it will have to be achieved with less water and fertilizer. Theoretical models suggest that for rice, an increase in yield of 50% accompanied by improvements in water and nitrogen use efficien- cies can be achieved only by converting rice from a C3 to a C4 plant. Such a feat will require the integration that problem as it exists now is sufficiently challenging, but what makes it even more daunting is that the problem is being magnified by a number of dynamic, aggravating features (Table 1). Over the next 50 years, the population of the world will increase by about 50%, climate change will likely result in more extreme variations in weather and cause adverse shifts in the world’s existing climatic patterns. Water scarcity will grow; the increasing demand for biofuels will result in competition between grain for fuel and grain for food resulting in price increases. Furthermore, more than 75% of the world’s people will live in cities, the popula- tions of which will need to be largely supported by a continuous chain of intensive food production and delivery. All of these adverse factors are growing now, at a time when the developed nations are both reducing their investments in agricultural research and turning their remaining research investments away from productivity gains (Pardey et al. 2006). If all of this was not bad enough the elite rice cultivars, which dominate the food supplies of the millions of poor people in Asia, have approached a yield barrier (Kropff et al. 1994) and the Green Revolution is slowing (Dawe 2007). Rice, wheat, maize, millet, and sorghum provide 70% of the calories and up to 90% of all protein consumed by the world’s population. About half the world’s population has rice as the staple cereal and almost all of the 600 million tons of rice produced each year are consumed directly by humans.

Ninety-seven percent of the water on the earth is sea water, 2% is ice and there is rising competition for the remaining 1% which is needed not only for agriculture and human consumption, but also for of efforts from those engaged in fundamental and applied research in many different countries; particularly those engaged in research concern- ing photosynthesis. All forms of research require funding, but funding mechanisms to both integrate and sustain the fundamental and applied research required to produce C4 rice, across national and disciplinary boundaries are almost non-existent.

The questions addressed in this paper are: (1) is it feasible to build a C4 rice using existing tech- nologies; (2) would it really deliver a simultaneous quantum increase in yield, water-use efficiency and nitrogen-use efficiency; and (3) what would be the cost-benefit ratio? Furthermore, I hope to demon- strate that it can be done on a time scale relevant to food security during the next half century. Failure, in this endeavor will mean a huge increase in human misery, a massive loss of natural environments and its associated negative impact on climate change.

The green revolution exhausted

The Green Revolution in Asia began at the International Rice Research Institute (IRRI) in the

1960s. It was based on the development of erect- leaved, semi-dwarf rice cultivars that had higher harvest indices and were much more fertilizer responsive than the traditional cultivars. The Green Revolution more than doubled food supply in Asia in 25 years, with an increase of only 4% in net cropped area (Lipton 2007; Rosegrant and Hazell 2000). Since the early eighties the impact of green revolution rice has been slowing down.

Sakamoto et al. (2006) suggested manipulat- ing brassinosteroid levels could improve erect leaf erectness and hence improve yield in elite rice. However, plant breeders have been selecting for canopy erectness for many years (Sheehy and Cooper 1973; Khush 2000). Measurements of the extinction coefficient (k) for photosynthetically active radiation in a rice canopy of the elite indica cultivar IR72 (Sheehy et al. 2007a) showed that k varies with solar elevation; the variation was more marked in clear conditions than overcast conditions. This means the apparent erectness of the canopy varies with solar elevation, appearing to be more prostrate earlier in the morning and more erect closer to noon. At noon, when the sun is directly overhead, the leaves of the IR72 rice canopy, when calculated from the k values, have an inclination of about 79° to the horizontal. It must be remembered that structures other than leaves intercept light so, in the calculation of k, the leaves appear to be more prostrate to compensate for the interception by those structures. Canopy ‘gross’ photosynthesis (Pc) can be calculated using the equation of France and Thornley (1984).

The maximum yields and radiation-use effi- ciencies of rice and maize growing unrestricted by water and nutrients in the dry season in the tropics were measured concurrently (Sheehy et al. 2007a). The radiation use efficiencies of maize and rice were 4.4g DW MJ?1 and 2.9g DW MJ?1 respectively; the ratio of the values was 1.52. At 14% moisture content the grain yield for maize was 13.9t ha?1 and for rice was 8.3t ha?1. Rice growing unrestricted by water and nutrients reached a yield limit set by canopy photosynthesis that was about 60% of that achieved by maize.

The results presented here suggests that the gains made from the original Green Revolution technologies centered on canopy architecture and crop nutrition have been fully exploited (Dawe 2007; Sheehy et al. 2007a).

Powering a second green revolution

Significant future yield improvements in rice must come from increases in canopy photosynthesis of a magnitude comparable to a change from C3 to C4 photosynthesis. The C4 system is seen as an addition to the C3 system and the repeated evolu- tion of C4 photosynthesis indicates it should be possible to create C rice by engineering C genes are not as rigidly separated as once thought. There is a well developed C4 pathway in green tissue around vascular bundles and rice spikelets and in the opposite direction in maize there patches of C3 tissue wherever a mesophyll cell is not adjacent to a bundle sheath cell. The culms of Eleocharis vivipara switch from C3 when submerged to C4 with Kranz anatomy when they are terrestrial and the cells of Hydrilla verticillata switch between C3 and C4 modes of photosynthesis depending on environmental conditions

Currently, it is not clear whether a single-cell system of C4 photosynthesis, a non-C4 method or a full Kranz C4 system will be sufficient to power the yields required later this century; each approach is discussed in Sheehy et al. (2007b). However, it is worth remembering that the full

C4 system brings with it not only high yields, but also better use of water and nitrogen fertilizer.

Constraints on progress towards C4 rice

In the absence of evidence to the contrary, it is easy to suggest that the construction of C4 rice would be difficult and the cost would be unusually high for agricultural research. However, the required knowledge is available, or becoming available and essential techniques in genetic engineering are advancing rapidly. The various strategies to be adopted to make C4 rice a reality over the next 10–15 years are discussed by an international group of scientists in Sheehy et al. (2007b).

There are a number of initial hurdles to be overcome in constructing a truly international collaborative program with the aim of producing C4 rice. The immediate challenge is to establish a funding bridge that enables researchers to come together as a functioning team. That team can then provide the proof of concept required to facilitate the large investment necessary for the production of C4 rice. It is constructive to compare scientific challenges of a comparable magnitude in the life sciences in terms of their impact on humanitarian problems and the funding available to solve those problems. Table 2 shows that the money spent annually on research aimed at curing malaria or HIV/AIDS far exceeds that spent on C4 rice; it is clear that the major funding obstacle to producing C4 rice is the small scale of funding available for research in the agricultural sciences. The economic benefits that would flow from a C4 rice are sub- stantial, the benefits accruing from increases in yield, water and nitrogen fertilizer savings would amount to many billions of dollars annually. The likely cost of constructing a C4 rice is of the order of hundreds of millions of dollars; the cost-benefit ratio is enormous.

The imperative for converting the photosyn- thetic system in rice from C3 to C4 is necessity rather than curiosity. It is not good enough to be optimistic that ‘business as usual’ will solve the problem of increasing rice yield. New and possibly radical approaches need to be explored urgently.

References

1. Cassman KG (ed) (1994) Breaking the yield barrier. Proceedings of a Workshop on Rice Yield Potential in Favorable Environments. International Rice Research Institute, Los Baños, Philippines, p 141.
2. Costanza R, d’Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O’Neill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M (1997) The value of the world’s ecosystem services and natural capital. Nature 387:253–260.
3. Dawe D (2007) Agricultural research, poverty alleviation, and key trends in Asia’s rice economy. In: Sheehy JE, Mitchell PL, Hardy B (eds) Charting New Pathways to C4 Rice. International Rice Research Institute, Los Baños, Philippines, pp 37–53.
4. de Haan C, Steinfeld H, Blackburn H (1997) Livestock and the environment: Finding a balance. Report of a study coordinated by the Food and Agriculture Organization of the United Nations, the United States Agency for International Development, and the World Bank. European Commission Directorate-General for Development, Brussels.
5. Evans JR, Von Caemmerer S (2000) Would C4 rice produce more biomass than C3 rice? In: Sheehy JE, Mitchell PL, Hardy B (eds) Redesigning Rice Photosynthesis to Improve Yield, Proceedings of the Workshop on the Quest to Reduce Hunger:

Redesigning Rice Photosynthesis, 30 Nov–3 Dec 1999, Los Baños, Philippines. International Rice Research Institute, Makati City, Philippines/Elsevier, Amsterdam, The Netherlandspp 53–71.

6. France J, Thornley JHM (1984) Mathematical Models in Agriculture. Butterworth, London, p 335, Gates FoundationGrants(2005)http://www.gatesfoundation.org/ GlobalHealth/Pri_Diseases/Malaria/Announcements/ Announce-051030.htm
7. Kebeish R, Niessen M, Thiruveedhi K, Bari R, Hirsch H-J, Rosenkranz R, Stäbler N, Schönfeld B, Kreuzaler F, Peterhänsel C (2007) Chloroplastic photorespiratory bypass increases photosynthesis and biomass pro- duction in Arabidopsis thaliana. Nature Biotechnol 25:593–599.
8. Khush GS (2000) Strategies for increasing the yield potential of rice. In: Sheehy JE, Mitchell PL, Hardy B (eds) Redesigning Rice Photosynthesis to Improve Yield, Proceedings of the Workshop on the Quest to Reduce Hunger: Redesigning Rice Photosynthesis, 30 Nov–3 Dec 1999, Los Baños, Philippines. International Rice Research Institute,
9. Makati City, Philippines/Elsevier, Amsterdam, The Netherlands, pp 207–212.
10. Kropff MJ, Cassman KG, Peng S, Matthews RB, Setter TL (1994) Quantitative understanding of yield potential. In: Cassman KG (ed) Breaking the Yield Barrier, Proceedings of a Workshop on Rice Yield Potential in Favorable Environments. International Rice Research Institute, Los Baños, Philippines, pp 21–38.
11. Lipton M (2007) Plant breeding and poverty: Can transgenic seeds replicate the ‘green revolution’ as a source of gains for the poor? J Dev Stud 43:31–62.
12. Noble IR, Dirzo R (1997) Forests as human-dominated eco- systems. Science 277:522–525.
13. Pardey PG, Alston JM, Piggott RR (eds) (2006) Agricultural R&D in the Developing World. International Food Policy Research Institute, Washington, DC, p 372.
14. Rosegrant M, Hazell P (2000) Transforming the rural Asian economy: The unfinished revolution. Oxford University Press, Hong Kong, for the Asian Development Bank, p 512.
15. Rothschild GHL (1996) Perspective for rice production in Asia. In: Ishii R, Horie T (eds) Crop research in Asia: Achievements and perspective, Proceedings of the 2nd Asian Crop Science Conference. Fukui, Japan, pp 12–17.
16. Sakamoto T, Morinaka S, Ohnishi T, Sunohara H, Fujioka S, Ueguchi-Tanaka M, Mizutani M, Sakata K, Takatsuto S, Yoshida S, Tanaka H, Kitano H, Matsuoka M (2006) Erect leaves caused by brassinosteroid deficiency increase biomass production and grain yield in rice. Nature Biotechnol 24:105–109.
17. Sheehy JE, Cooper JP (1973) Light interception, photosyn- thetic activity, and crop growth rate in canopies of six temperate forage grasses. J Appl Ecology 10:239–250.
18. Sheehy JE, Mitchell PL, Dionora MJA, Tsukaguchi T, Peng SB, Khush GS (2000) Unlocking the yield barrier in rice through a nitrogen-led improvement in the radia- tion conversion factor. Plant Prod Sci 3:372–374.
19. Sheehy JE, Dionora MJA, Mitchell PL (2001) Spikelet numbers, sink size and potential yield in rice. Field Crop Res 71:77–85.
20. Sheehy JE, Ferrer AB, Mitchell PL, Elmido-Mabilangan A, Pablico P, Dionora MJA (2007a) How the rice crop works and why it needs a new engine. In: Sheehy JE, Mitchell PL, Hardy B (eds) Charting New Pathways to C4 Rice. International Rice Research Institute, Los Baños, Philippines, pp 3–26.
21. Sheehy JE, Mitchell PL, Hardy B (eds) (2007b) Charting New Pathways to C4 Rice. International Rice Research Institute, Los Baños, Philippines, p 422.

22. Suzuki S, Murai N, Burnell JN, Arai M (2000) Changes in photosynthetic carbon flow in transgenic rice plants that express C4-type phosphoenolpyruvate carboxykinase from Urochloa panicoides. Plant Physiol 124:163–172.