Opinion

Can GM sorghum impact Africa?

Gerda M. Botha and Christopher D. Viljoen

GMO Testing Facility, University of the Free State, PO Box 339, Bloemfontein 9300, South Africa

It is said that genetic modification (GM) of grain sorghum has the potential to alleviate hunger in Africa. To this end, millions of dollars have been committed to developing GM sorghum. Current developments in the genetic engineering of sorghum are similar to efforts to improve cassava and other traditional African crops, as well as rice in Asia. On closer analysis, GM sorghum is faced with the same limitations as 'Golden Rice' (GM rice) in the context of combating vitamin A deficiency (VAD) efficiently and sustainably. Thus, it is questionable whether the cost of developing GM sorghum can be justified when compared to the cost of investing in sustainable agricultural practice in Africa.

Introduction

Considering that over 4.3 million people in Southern Africa are currently surviving on food donations, the genetic engineering of sorghum holds promise for the alleviation of hunger and improved nutrition (http://www.wfp.org). The onset of the 'green revolution' in the 1940s and its continuation through to the 1960s provided food security for developed countries through the use of mechanization, irrigation schemes and synthetic fertilizers and pesticides [1–3]. However, resource-poor Africa did not participate in or benefit from agricultural industrialization [1,2,4]. The application of recombinant DNA technology in traditional African crops, especially sorghum, is considered to represent a second 'green revolution' that will 'benefit those passed by the first' (http://www.nuffieldbioethics.org). Thus, genetic modification (GM) holds the potential to improve the livelihoods of resource-poor farmers and to dramatically increase the average yield of the poorest countries in Africa.

Sorghum (*Sorghum bicolor* (L)), after maize, wheat, rice and barley, is the fifth most important grain crop in the world and the second most produced grain on the African continent (http://faostat.fao.org). In Africa, sorghum is used for food and feed and is adapted to growing in marginal and drought-stricken areas [5–7]. Sorghum is used in the production of traditional foods and beer, as well as in the production of commercial beer and non-traditional products such as instant porridges [8]. In the developed world, sorghum is produced by commercial farmers, predominantly for animal feed. In Africa, it is produced mainly by subsistence farmers and consumed by more than 500 million people in more than 30 countries, of which Nigeria, Sudan and Ethiopia are the highest producers (http://faostat.fao.org). In 2005, Africa produced 22 million tonnes of grain sorghum compared to the 10 and 11 million tonnes produced by Asia and the US, respectively. Despite high production in Africa, yield is low with an average of 0.85 tonnes/ha of sorghum recorded in 2006 for central Africa, compared to 1.03 tonnes/ha in Asia and 4.31 tonnes/ha in the US (http://faostat.fao.org). The elevated yield in the US is the result of using improved varieties rather than just favourable environmental conditions. With the introduction of the combine harvester in 1960, cultivars in the US have been specifically developed for higher yield through conversion programs [5,9,10]. These conversion programs made use of African germplasm to breed improved varieties for US agriculture [11]. Unfortunately, Africa never really benefited from these programs, and traditional African cultivars are not high yielding [12,13]. Although sorghum breeding programmes were implemented in Africa in the late 1980s, the net outcome has had little effect because of a lack of distribution mechanisms and supporting infrastructure [7,12]. For example, in 1985 a sorghum germplasm collection at Ilonga Research Institute in Tanzania was destroyed because of a power failure [6]. In another example, a higher yielding variety developed by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) was only released in Tanzania eleven years after its development [14]. Thus, sorghum breeding in Africa has not had the intended effect [7].

Recently, the Bill and Melinda Gates Foundation made a US$450 million commitment to the African Biotechnology Sorghum (ABS) project (http://www.supersorghum.org). This project is also supported by an additional US$27.1 million from the Wellcome Trust, as well as US$4.5 million from the Canadian Institute of Health Research [15]. The project consists of a consortium including Pioneer Hi-Bred (a Dupont subsidiary), the University of California, three South African institutions and three other African members (Table 1). Although the project management resides with Africa Harvest, which is responsible for the overall coordination and implementation of the programme, Pioneer Hi-Bred International provides the scientific leadership as principle investigator, and product development is provided by the CSIR (Council for Science and Industrial Research), through which Pioneer Hi-Bred will facilitate technology transfer (http://www.supersorghum.org). The overall aim of this project is to use transgenic technology to improve the health and wealth of people in the world's poorest countries by means of a more nutritious and easily digestible sorghum (cooked sorghum is less digestible compared to other cereals) that would contain increased levels of essential amino acids, especially lysine, and increased levels of vitamins A and E, as well as increased availability of iron and zinc [15,16]. The ABS project justifies its objectives by citing the success of transgenic maize, and claims that the same technology will result in the significant improvement of sorghum [17].

Corresponding author: Botha, G.M. (bothagm.sci@mail.ufs.ac.za).

0167-7799/$ – see front matter © 2007 Elsevier Ltd. All rights reserved. doi:10.1016/j.tibtech.2007.10.008 Available online 11 January 2008

Table 1. ABS Project consortium partners

Consortium partner	Function
Project steering committee	
Africa Harvest Biotech Foundation International (AHBFI)	• Overall project coordination • Product development, technical affairs, finance and business development, communications and public acceptance and regulatory affairs
DuPont, through Pioneer Hi-Bred	• Intellectual property • Principal Investigator providing scientific leadership
Council for Science and Industrial Research (CSIR)	• Technology transfer
Additional consortium members	
International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)	• Product development, laboratory and field trials
African Agricultural Technology Foundation (AATF)	• Managing technology audits and the negotiation of intellectual property
Forum for Agricultural Research in Africa (FARA), the technical partner of New Partnership for Africa's Development (NEPAD)	• Developing an appropriate product distribution mechanism
University of Pretoria (UP)	• Nutritional analysis, as well as the development of food preparation techniques and menus
Agricultural Research Council (ARC)	• Community input and participation in project design
University of California, Berkeley (UC Berkeley)	• Research into improving the digestibility of sorghum

Thus, the nutritional improvement of transgenic sorghum is comparative to current efforts to combat vitamin A deficiency (VAD) through transgenic rice.

Vitamin-enriched GM rice

It is estimated that over 2 million people go blind each year, and 60% of the cases in India, China and sub-Saharan Africa are a result of VAD (http://www.unsystem.org/scn) [18,19]. Interventions to prevent VAD-associated blindness include health-care education, vitamin supplementation, home gardening, nutritional feeding programs and GM rice containing enhanced levels of pro-vitamin A (http://www.unsystem.org/scn) [18,20].

The United Nations Standing Committee on Nutrition (SCN) has emphasized the need for 'integrated interventions' in combating nutritional deficiencies (http://www.unsystem.org/scn). Vitamin supplementation has already had a substantial impact in alleviating VAD amongst children in projects in Nepal and Bangladesh (http://www.unsystem.org/scn) [20,21]. However, the use of supplements is not without problems and needs to be accompanied by nutrition education, training of health-care workers and adequate access to households (http://www.unsystem.org/scn) [22–25].

GM rice, known as 'Golden Rice' because of its yellow colour, has been developed to produce enhanced levels of pro-vitamin A (β-carotene) [26]. Because of low expression levels in the first version of Golden Rice, 'Golden Rice 2' was developed with a reported 37-fold increase in β-carotene [22]. Golden Rice is the first example of a GM crop that provides a direct benefit to consumers, something that first generation GM crops have failed to do [22,23,27]. This rice has been publicized as being able to prevent blindness and death for millions of the 'poorest of the poor' [23–27].

Golden Rice faces similar problems in Asia as GM sorghum would in Africa. These include concerns over the environment, patents, efficacy and social acceptance. In terms of the environment, there is a concern that Golden Rice will contaminate traditional varieties as well as wild relatives, which could have catastrophic consequences because Asia is the centre of origin for rice [28,29]. Although marketed as royalty free, Golden Rice is controlled by several international patents held by multinational companies. To accommodate resource-poor farmers, these companies have generously agreed to waiver royalties, as long as earnings from the GM rice are less than US$10 000 a year per farmer and the product is not exported (http://www.econexus.info). However, this might not be practical as it is doubtful whether farmers would have the management resources to prove that the income generated by GM-enhanced rice, compared to total income, is below the threshold that requires royalty payments.

Although Golden Rice is being suggested as an alternative to vitamin supplementation for combating VAD, the principles of food nutrition are unfortunately being overlooked [30]. β-Carotene undergoes several enzymatic reactions before being converted to retinol, the form of vitamin A absorbed by the body. As a result, the general bioavailability of vitamin A from β-carotene is 10% or less [31,32]. The recommended dietary allowance (RDA) of vitamin A is between 700 and 900 μg retinol per day [31]. Thus, a person would need to consume 250 g of uncooked Golden Rice 2 per day (assuming a maximum content of 37 μg/g β-carotene, although the average reported was 17.7 μg/g) to achieve the required RDA, assuming a 10% efficiency in conversion [22]. Furthermore, the conversion of β-carotene to vitamin A requires the presence of lipids, especially unsaturated fatty acids [33,34]. In a study on humans performed by Tang *et al.* [35], it was reported that the conversion of β-carotene (from Golden Rice) to retinol was found to be equivalent whether given in single or multiple meals with the supplementation of fat, 10 g and 2.5 g, respectively. Ironically, brown rice already contains β-carotene and the required lipids for bioconversion on the inner layers of the husk. However, this is removed during milling to produce white rice, which is preferred to brown rice [34]. Although Golden Rice contains β-carotene in the endosperm, which is not lost during milling, it does not contain the fatty acids required for absorption. In addition, because of its golden colour, Golden Rice might be as socially unacceptable as brown rice owing to cultural preferences (http://biotech-info.net/costs.html, http://www.panap.net, http://home.worldcom.ch/negenter/473bTx_E01.html). Furthermore, a study conducted by Stein *et al.* [36] concluded that although Golden Rice 2 might contribute to solving VAD, an array of approaches is still needed to deal with the complexity of the problem. The study also concedes that β-carotene bioavailability from Golden Rice 2 needs to be scientifically verified. Thus, given the problems with nutrition, bioavailability and social acceptance, it is questionable whether Golden Rice will have the intended effect on VAD. Similarly, GM sorghum faces many, if not all, of the problems associated with Golden Rice, and its actual ability to 'improve the lives of millions of the poorest people in the world' is also questionable [25].

Relevance of traits intended for GM sorghum

There is an important parallel between the application of GM sorghum in Africa and GM rice in Asia. Transgenic traits intended for sorghum include increased levels of vitamin A and E, increased availability of iron and zinc and improved protein quality. GM sorghum with agronomic traits such as herbicide tolerance (used as a genetic marker for gene transformation), insect resistance and increased lysine content have been developed but not released [37,38]. However, it is important to distinguish between GM traits that are suited to commercial agriculture and those that have relevance for subsistence farmers. For example, the vast majority of African farmers apply manual weeding because they do not have access to or the resources to acquire herbicides. Insect resistance has the potential to decrease crop losses from insect damage, but might also lead to the emergence of secondary pests [39]. Faria *et al*. [40] reported an increase in aphids on Bt maize and Ponsard *et al*. [41] observed a decrease in pest predators for Bt cotton. Thus, any shift in insect population levels or a loss of the natural control of pests could result in the requirement of additional insecticidal control, which would prove problematic for resource poor farmers [42].

Nutritional traits, such as Lysine, increased levels of vitamin A and E, increased levels of iron and zinc and improved protein quality, are important traits for the improvement of human nutrition in Africa. However, sustainable nutrition requires a well-balanced diet, and one food crop cannot replace all the vital components (http://www.unsystem.org/scn) [43]. Although not exploited, sorghum varieties with the potential for nutritional improvement have been identified that contain β-carotene (ranging from 0 to 1.132 μg/g), iron (ranging from 20.1 to 50.0 μg/g) and zinc (ranging from 13.4 to 31.0 μg/g), as well as vitamins B, D, E and K [44,45]. Ironically, none of the GM sorghum traits under development are aimed at increasing yield, which is one of the greater agronomic problems facing sorghum production in Africa. Although it has not been necessary to use GM sorghum to elevate yields in the US, which at 4.31 tonnes/ha is currently the highest in the world, it is thought that the introduction of GM sorghum can achieve higher productivity in Africa (http://www.fao.org).

Sustainability of GM sorghum in Africa

Although projects for developing GM sorghum have high and noble ideals, several different issues need to be addressed to ensure sustainability. These include the resource requirements of farmers, intellectual property rights and the impact of GM gene flow on the environment, as well as social acceptance of GM sorghum. The potential impact of GM technology must also be evaluated in the background of current limitations in agricultural practice in Africa.

Despite the potential impact that GM traits could have on sorghum production and nutrition, it is important to take cognisance of the actual needs of Africa in terms of sorghum improvement. In a study by Laswai *et al.* [46], several limitations associated with grain production were raised, including the availability of processing equipment, organized marketing and product development. In addition to this, specific constraints associated with sorghum farming include difficulties with grain storage, birds damaging kernel heads and a lack of processing facilities for de-hulling and threshing [46]. Maize is favoured by subsistence farmers in regions with sufficient rainfall, whereas sorghum is better adapted to withstand drought, high temperatures and water logging [7,47,48]. This highlights the reality that Africa is once again being given what the world thinks it needs and not what it actually needs.

Sorghum cultivation originated in Africa with the development of landraces (a farmer-developed cultivar that is adapted to local environmental conditions and that can also include preferred cultural characteristics) before the slave trade (http://faostat.fao.org). Cultivated sorghum (*Sorghum bicolor* subsp. *Bicolour*) comprises five main races, namely bicolour, kafir, guinea, durra and caudatum, specifically adapted to the different regions in Africa where they originated [5]. Gene flow from GM sorghum to landraces would threaten a valuable genetic resource [5,49]. A risk assessment by Schmidt and Bothma [49] determined that sorghum gene flow could occur within a radius of up to 2 km. Gene flow of traits, for example, insect resistance and herbicide tolerance, from GM sorghum to wild relatives, such as Johnsongrass (*Sorghum halepense*), could result in increased fitness, which would impact biodiversity and agricultural management [50,51]. Thus, the introduction of GM sorghum will definitely impact on gene flow to landraces and wild relatives.

Intellectual property rights and ownership through patenting is a concept that is totally alien in African culture. Thus, the requirement to pay royalties on patented seed becomes a barrier for farmers who wish to access recombinant DNA technology. A good case study for this is the introduction of Bt cotton to rural farmers in the Makhatini flats in South Africa in 1998 [52–54]. Although Bt cotton was quickly adopted, these farmers have had to deal with the increased cost of GM seed and an international slump in the price of cotton, resulting in increased debts [53]. The Makhatini farmers buy cotton seed every year only because de-linting the seed is too labour intensive. However, these farmers save and exchange maize seed. If GM maize were introduced to the Makhatini, it is difficult to see why this practice would cease or why farmers would agree to pay royalties on saved seed.

GM sweet potato can also be used as a model to assess the impact and acceptance of a GM African crop. A project was launched in 1995 by the Kenyan Agricultural Research Institute (KARI) and Monsanto to develop a transgenic virus-resistant sweet potato variety (http://allafrica.com/sustainable/resources/00010161.html). In 2000,

Table 2. Constraints and solutions surrounding the introduction of GM in Africa

Issues	Solutions
Farming resources	
• Lack of farming subsidies and access to credit • Farmers do not have ready access to agricultural inputs • Diverse farming communities consisting of mainly subsistence farmers	• Farming subsidies in the developed world should be eliminated and systems established to give African farmers access to resources without tying them into a cycle of debt
Variety improvement	
• There is not an effective system to ensure that new varieties are released to farmers • New varieties are often developed to suit commercial farming conditions • Breeding improvement does not always consider cultural preferences • Varieties developed in first world countries are not adapted to the African environment	• Variety improvement should begin by assessing the needs of the farmer and community • Programmes should incorporate farmers' knowledge of crops as well as locally adapted landraces
GM traits	
• The selection of GM traits is not based on identified needs	• Drought and heat tolerance as well as grain quality have been identified as important traits
Nutrition	
• One food crop cannot provide balanced nutrition	• Nutritional education is as important as technological solutions
Environmental management	
• Gene flow to wild relatives and landraces	• Implementation of guidelines by African governments for the safe application and use of biotechnology • Apply a precautionary approach to genetically engineering indigenous germplasm and landraces
Intellectual property rights	
• African countries cannot afford to access intellectual property owned by companies in developed countries	• An unconditional withdrawal of patents in developing countries or a complete waiver of all royalties

a virus-resistant GM variety was produced at an estimated cost of US$6 million. Although field trials have been ongoing, there is no expected release date for the GM variety (http://allafrica.com/sustainable/resources/00010161.html). It has been speculated that field trials failed because the virus resistance was designed to guard against a US strain of the sweet potato feathery mottle virus (SPFMV) and was ineffective for the African strain (http://www.twnafrica.org). Furthermore, the transgenic variety used was unpopular amongst farmers as it did not meet site specifications (http://allafrica.com/sustainable/resources/00010161.html). This emphasizes the need to modify solutions developed by the first world to conditions in the third world.

It is important to note that the majority of sorghum consumption in Africa is actually in the form of sorghum beer and traditional fermented foods, such as porridge, and this tradition is as old as sorghum cultivation [5,55]. Malting and fermentation of sorghum increases the nutritional value and protein quality and it is therefore questionable whether the enhanced nutrient content in GM varieties would have any further nutritional benefit [44,55]. It has also never been established whether the introduction of GM sorghum would be culturally acceptable. Furthermore, there is resistance to the introduction of GM in Africa (with South Africa being the exception), possibly due to a fear of the collapse of export markets [56]. If the applications for GM sorghum trials have proven unsuccessful in South Africa, which is considered 'GM friendly', it is unlikely that they will succeed elsewhere in Africa as a result of the environmental and economic concerns previously discussed [56].

Assessing the actual needs of Africa

Africa is poor in technological resources. Most countries lack basic infrastructure for agricultural management and practice. Crop varieties are in need of basic breeding improvement, especially in terms of yield and environmental adaptation, and this is not likely to be addressed by GM technology. Unlike farmers in the EU and US, African farmers are not subsidized, and basic chemical inputs are not affordable or readily available. Unfortunately, the same reasons for the failure of the green revolution in Africa also apply to GM. In addition to GM seed, farmers still require fertilizer, insecticides and herbicides to realize the benefits of GM technology. It is also not certain whether companies will waiver royalties as this has not been the case for farmers in the Makhatini. Furthermore, it must be recognized that poverty in Africa is exacerbated by social factors such as poor governance, corruption, armed conflict and lack of education [57]. Thus, for GM sorghum to have the desired impact, it needs to form part of an integrated approach that addresses the issues associated with agriculture in Africa (Table 2). This begs the question of whether the philanthropic donation of millions of dollars is just a publicity exercise to promote GM technology without taking into account the actual needs of Africa.

Acknowledgements

We would like to thank L. Chetty, J. van Deventer, G. Lampregt and N. Meintjies for valuable discussions and comments, as well as the anonymous reviewers.

References

1 Tilman, D. (1998) The greening of the green revolution. *Nature* 396, 211–212
2 Khush, G.S. (1999) Green revolution: preparing for the 21st century. *Genome* 42, 646–655
3 Evenson, R.E. and Gollin, D. Assessing the impact of the Green Revolution, 1960 to 2000. *Science* DOI:10.1126science.1078710 (http://www.sciencemag.org)
4 Buttel, F.H. *et al.* (1985) From Green Revolution to Biorevolution: some observations on the changing technological bases of

economic transformation in the third world. *Econ. Dev. Cult. Change* 34, 31–55

5 Doggett, H. (ed.) (1988) *Sorghum*, Longman Scientific & Technical, John Wiley & Sons inc.

6 Mansuetus, S.B.A. (1995) Sorghum diseases in Tanzania. *African Crop Sci. J.* 3, 203–207

7 House, L.R. (1995) Sorghum: one of the world's great cereals. *African Crop Sci. J.* 3, 135–142

8 Taylor, J. and Dewar, J. (2000) Fermented products: beverages and porridges. In *Sorghum: Origin, History, Technology, and Production* (Smith, C.W. and Frederiksen, R.A., eds), pp. 751–795, New York, John Wiley & Sons

9 Miller, F.R. (1982) Genetic and environmental response characteristics of sorghum. In *Sorghum in the Eighties: Proceedings of The International Symposium on Sorghum*, pp. 393–402, India, Patancheru

10 Rosenow, D.T. and Dahlberg, J.A. (2000) Collection, conversion and utilisation of sorghum. In *Sorghum: Origin, History, Technology and Production* (Wayne Smith, C., ed.), pp. 309–323, John Wiley & Sons Inc.

11 Duncan, R.R. *et al.* (1991) Contributions of introduced sorghum germplasm to hybrid development in the USA. In *CSSA Special Publication No 17*, Crop Science Society of America

12 Carr, S.J. (1997) A green revolution frustrated: lessons from Malawi experience. *African Crop Sci. J.* 5, 93–98

13 Mgonja, M.A. *et al.* (2005) Stratification of SADC regional sorghum testing sites based on grain yield of varieties. *Field Crops Res.* 96, 25–30

14 Mgonja, M.A. (2003) Getting it right: improving the efficiency of regional crop breeding and seed systems in southern Africa. *SA Trends ICRISAT's monthly newsletter* 27, 1

15 O'Kennedy, M.M. *et al.* (2006) Harnessing sorghum and millet biotechnology for food and health. *J. Cereal Sci.* 44, 224–235

16 Dewar, J. (2003) Influence of malting on sorghum protein quality. In *Conference Proceedings of the Afripro Workshop on the Proteins for Sorghum and Millets: Enhancing Nutritional and Functional Properties for Africa: 2003 April 2–4* (Belton, P.S. and Taylor, J.R.N., eds), paper 18, Conference proceedings Afripro workshop

17 Jung, R. (2006) The African Biofortified Sorghum Project – applying biotechnology to develop nutritionally improved sorghum for Africa. In *World Grains Summit: Foods and Beverages: 2006 September 17–20; San Francisco, California*. Session 125 (http://www.aaccnet.org/meetings/2006/abstracts)

18 Gilbert, C. and Foster, A. (2001) Childhood blindness in the context of VISION 2020 – the right to sight. *Bull. World Health Organ.* 97, 227–232

19 Spivey, B. (2001) The opportunity for international ophthalmology in treating blindness. *Tr. Am. Ophth. Soc* 99, 73–77

20 Ahmed, F. (1999) Vitamin A deficiency in Bangladesh: a review and recommendations for improvement. *Public Health Nutr.* 2, 1–14

21 Bishai, D. *et al.* (2005) The impact of vitamin A supplementation on morality inequalities among children in Nepal. *Health Policy Plan.* 20, 60–66

22 Paine, J.A. *et al.* (2005) Improving the nutritional value of Golden Rice through increased pro-vitamin A content. *Nat. Biotechnol.* 23, 482–487

23 Potrykus, I. (2001) Golden Rice and beyond. *Plant Physiol.* 125, 1157–1161

24 Greger, J.L. (2000) Mobilizing dieticians to be a resource. *J. Am. Diet. Assoc.* 100, 1306–1307

25 Nash, M.J. (2000) Grains of hope, *Time* 31 July, pp. 396–404

26 Ye, X. *et al.* (2000) Engineering the provitamin A (β-carotene) biosynthetic pathway into (carentonoid-free) rice endosperm. *Science* 287, 303–305

27 Datta, K. *et al.* (2003) Bioengineered 'golden' indica rice cultivars with β-carotene metabolism in the endosperm with hygromycin and mannose selection systems. *Plant Biotechnol. J.* 11, 81–90

28 Lu, B-R. *et al.* (2003) Can transgenic rice cause ecological risks through transgene escape? *Prog. Nat. Sci.* 13, 17–24

29 Chen, L.J. *et al.* (2004) Gene flow from cultivated rice (*Oryza sativa*) to its weedy and wild relatives. *Ann. Bot. (Lond.)* 93, 67–73

30 Ross, D.A. (2002) Recommendations for Vitamin A supplementation. *J. Nutr.* 132 (Suppl. 9), 2902S–2906S

31 IOM (Institute of Medicine) (2002). Dietary reference intakes for vitamin A, vitamin K, arsenic, boron, chromium, copper, iodine, iron, manganese, molybdenum, nickel, silicon, vanadium and zinc. In *Report of the Panel on Micronutrients Subcommittees on Upper Reference Levels of Nutrients and of Interpretation and Uses of Dietary Reference Intakes* (Food and Nutrition Board, Institute if Medicine (U.S.), eds), pp. 82–84, National Academy Press

32 Nestle, M. (2001) Genetically engineered "golden" rice unlikely to overcome vitamin A deficiency. *J. Am. Diet. Assoc.* 101, 289–290

33 Olson, J.A. (1998) Carotenoids. In *Modern Nutrition in Health and Disease* (9th edn) (Shils, M.E., Olson, J.A., Shike, M. and Ross, C.A., eds), pp. 525–541, Philadelphia Lippincott Williams and Wilkins

34 Frei, M. and Becker, K. (2004) Agro-biodiversity in subsistence-orientated farming systems in a Philippine upland region: nutritional considerations. *Biodivers. Conserv.* 13, 1591–1610

35 Tang, G. *et al.* (2006) Quantitative determinations of Vitamin A value of Golden Rice given as single or multiple meals. In *Micronutrient forum: 2007 April 18*. Poster number W29

36 Stein, A.J. *et al.* (2006) Potential impact and cost-effectiveness of Golden Rice. *Nat. Biotechnol.* 24, 1200–1201

37 Zhao, Z-Y. *et al.* (2000) Agrobacterium-mediated transformation. *Plant Mol. Biol.* 44, 789–798

38 Zhao, Z-Y. *et al.* (2002) Nutritional improved transgenic sorghum. In *Plant Biotechnology 2002 and Beyond proceedings of the 10th IAPTC&B Congress* (Vasil, I.K., ed.), pp. 413–416, Kluwer Academic Publishers

39 Gutierrez, A.P. *et al.* (2006) Physiologically based demographics of Bt cotton-pest interactions II. Temporal refuges, natural enemy interactions. *Ecol. Modell.* 191, 360–382

40 Faria, C.A. *et al.* (2007) High susceptibility of Bt maize to aphids enhances the performance of parasitoids of Lepidopteran pests. *PLoS ONE*,2, 600 DOI: 10.1371/journal.phone.0000600 In: http://www.plosone.org)

41 Ponsard, S. *et al.* (2002) Effect of Bt-toxin (Cry1Ac) in transgenic cotton on the adult longlivety of four Heliopteran predators. *Environmental Entomology* 31, 1197–1205

42 Morse, S. *et al.* (2006) Environmental impact of genetically modified cotton in South Africa. *Agric. Ecosyst. Environ.* 117, 277–289

43 Rigby, M. (2005) Child health indicators of life and development and the challenge of nutrition. *J. Public Health (Bangkok)* 13, 84–88

44 Léder, I. (2004) Sorghum and millets. In *Cultivated Plants, Primarily as Food Sources* (G. Füleky., ed.) in Encyclopedia of Life Support Systems (EOLSS), Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford

45 Reddy, B.V.S. *et al.* (2005) Prospects of breeding for micronutrients and b-carotene-dense sorghum. *International Sorghum and Millets Newsletter* 46, 11–14

46 Laswai, H.S. *et al.* (2003) Collaborative project to investigate consumer preferences for selected sorghum and millet products in the SADCC region of Africa. In *Conference Proceedings of the Afripro Workshop on the Proteins for Sorghum and Millets: Enhancing Nutritional and Functional Properties for Africa: 2003 April 2–4* (Belton, P.S. and Taylor, J.R.N., eds), paper 07, Conference proceedings Afripro workshop

47 Ellstrand, N.C. *et al.* (1999) Gene flow and introgression from domesticated plants into their wild relatives. *Annu. Rev. Ecol. Evol. Syst.* 30, 539–563

48 Chisi, M. (2003) Collaborative project to investigate consumer preferences for selected sorghum and millet products in the SADCC region of Africa. In *Conference Proceedings of the Afripro Workshop on the Proteins for Sorghum and Millets: Enhancing Nutritional and Functional Properties for Africa: 2003 April 2–4* (Belton, P.S. and Taylor, J.R.N., eds), paper 15, Conference proceedings Afripro workshop

49 Schmidt, M. and Bothma, G. (2006) Risk assessment of transgenic sorghum in Africa: crop-to-crop gene flow in *Sorghum bicolor* (L.). *Moench. Crop Sci.* 46, 790–798

50 Arriola, P.E. and Ellstrand, N.C. (1997) Fitness of interspecific hybrids in the genus sorghum: persistence of crop genes in wild populations. *Ecol. Appl.* 7, 512–518

51 Jenczewski, E. *et al.* (2003) Crop-to-wild gene flow, introgression and possible fitness effects of transgenes. *Environ. Biosafety Res.* 2, 9–24

52 Ismael, Y. *et al.* (2002) Benefits from Bt cotton use by smallholder farmers in South Africa. *AgBioForum* 5, 1–5

53 Hofs, J. *et al.* (2006) Impact of Bt cotton adoption on pesticide use by smallholders: A 2-year survey in Makhatini Flats (South Africa). *Crop Prot.* 25, 984–988

54 Thirtle, C. *et al.* (2003) Can GM-technologies help the poor? The impact of Bt cotton in Makhatini Flats, KwaZulu-Natal. *World Dev.* 31, 717–732

55 Belton, P. (2003) The improvement of the protein quality of sorghum and its introduction into staple food products for Southern and Eastern Africa. In *Conference Proceedings of the Afripro Workshop on the Proteins for Sorghum and Millets: Enhancing Nutritional and Functional Properties for Africa: 2003 April 2–4* (Belton, P.S. and Taylor, J.R.N., eds), paper 04 Conference proceedings Afripro workshop

56 Zerbe, N. (2004) Feeding the famine? American food aid and the GMO debate in Southern Africa. *Food Policy* 29, 539–608

57 Robinson, J. (1999) Ethics and transgenic crops: a review. *Electron. J. Biotechnol.* 2, 71–81