GM Nitrogen Fixing Cereals: No silver bullet

October 2012

Summary

GM nitrogen fixation in cereals like maize and wheat has become the "holy grail" of biotechnologists. An example of the interest in the approach is the Bill and Melinda Gates Foundation research grant of US$10 million to the UK's John Innes Centre.

Major obstacles stand in the way of GM nitrogen fixing crops, including difficulties in genetically modifying both a crop plant and a nitrogen fixing bacterium to work symbiotically together. Achieving this will involve multiple genetic modifications and, if successful, would place a large energy demand on the plant, which could in turn result in lower yields. Such a major change in what the plant wants to do naturally could lead to unintended consequences, too, such as susceptibility to a wider range of pests and diseases than are currently important on cereals.

Even if the technology does work, GM nitrogen fixing crops will take decades to perfect and absorb millions of pounds in research and development funding that would be better spent on projects with a much higher probability of successfully addressing a wider range of agronomic problems. It could prove to be an expensive and unnecessary diversion.

Nitrogen is an essential nutrient for plants, and biological nitrogen fixation already takes place in leguminous plants (eg, peas and beans). These plants evolved a symbiotic association with *Rhizobium* bacteria, which inhabit root nodules in the plants. In return for the plant supplying the bacteria with energy-rich carbohydrates, the bacteria convert atmospheric nitrogen into ammonia, which can then be taken up and used by the plant in the form of nitrates.

There is no shortage of nitrogen in the world, but it is managed extremely poorly. Modern intensive monoculture arable systems growing cereals often do not include legumes in crop rotations, so the potential for solar powdered nitrogen fixation is not being fully exploited. Nitrogen has become a major pollutant of the atmosphere, fresh water and marine ecosystems, and it has now exceeded the global limits of natural systems to deal with this pollution. The efficient recovery of nitrogen in "waste" so that it can be recycled back into agricultural soils should be a major policy and research priority, along with the restoration of soils using proven agroecological techniques to improve soil structure and fertility. The agroecological approach also tackles other problems that GM nitrogen fixation cannot, like maintaining or increasing mineral nutrients in soils.

The use of GM nitrogen fixing cereals (if it proves possible with acceptable yields) would further increase the use of industrial monoculture farming. It could tempt farmers into adopting shorter crop rotations, which would exacerbate soil fertility, disease and weed problems. Availability of GM nitrogen fixing cereals would probably also lead to the expanded use of other GM traits (eg, herbicide tolerance). These GM traits have already been widely deployed in North and South America, and as a result major weed resistance problems have developed. The use of numerous GM glyphosate resistant strains is causing a significant escalation of herbicide use on these crops (eg, Monsanto's RR maize, soybeans and cotton), with consequent escalations in glyphosate pollution and residues on food and animal feed.

Governments, the GM industry, some academics and some vocal funders are seeking a 70-100% increase in yields in countries where soils are poor and farmers cannot afford to apply artificial fertilisers. This is far from inevitable. In richer countries the quest for nitrogen fixing cereals is one symptom of a weakened food production system that needs to be addressed in the round, rather than with technofixes, if agriculture is to be sustainable and remain within planetary limits. There is already more than enough food available to feed everyone on the planet without. It is a lack of political will that prevents the socioeconomic, trade and agricultural changes required to feed everyone. Relying on a mirage like GM nitrogen fixing cereals is not the answer.

GM Freeze 50 South Yorkshire Buildings, Silkstone Common, Barnsley S75 4RJ
Tel: 0845 217 8992 **Email:** info@gmfreeze.org **Web:** www.gmfreeze.org **Twitter:** @GMFreeze

Introduction

> *"GM nitrogen fixing crops are not the answer to improving the fertility of Africa's soils. African farmers are the last people to be asked about such projects. This often results in the wrong technologies being developed, which many farmers simply cannot afford.*
>
> *"We need methods that we can control aimed at building up a resilient soil that is both fertile and able to cope with extreme weather. We also want to receive some respect for our knowledge and skills and not have inappropriate solutions imposed upon by distant institutions, charitable bodies and governments."*
>
> - Miriam Mayet, African Centre for Biosafety

The prospect of genetically modifying cereal crops so they are able to fix atmospheric nitrogen in the way legumes do has generated a lot of publicity. The Bill and Melinda Gates Foundation recently allocated US$10 million to the UK's John Innes Centre to research genetically modifying nitrogen fixation into maize for sub-Saharan African farmers.[i]

This document outlines a number or reasons why this is not a good idea, is unnecessary and may well not work, wasting millions that should be better spent elsewhere.

Nitrogen fixation

Nitrogen fixation is naturally carried out by bacteria. Some are free-living in the soil or water, and others are in symbiotic association with plants or other organisms, such as protozoa. Nitrogen fixation in symbiotic associations fixes much more that free-living systems.

Nitrogen fixation in plants involves a symbiotic relationship between the plant and a soil bacterium (either *Rhizobium or, in chickpeas and soybeans, Bradyrhizobium, or in woody plants Franki).* Atmospheric nitrogen is an inert gas, and nitrogen fixation makes it available for plants to take up and use either as ammonium (NH_4) or nitrate (NO_3, ammonium converted to nitrate by soil-dwelling nitrifying bacteria).

In legumes (eg, clover, peas and beans) the bacteria invade the root hairs stimulating the formation of specialised organs called nodules, which the bacteria then inhabit independently contained within a membrane. Here they convert atmospheric nitrogen into ammonia using the enzyme nitrogenase.

Nitrogenase is only found in bacteria and is not produced by plants. Although it is deactivated in the presence of oxygen, nitrogen fixation is most efficient in the presence of oxygen. To enable this to work the plant and bacteria combine to form an oxygen-carrying haemoglobin-like protein called leghaemoglobin, which is unique to root nodules. Lehaemoglobin allows an oxygen concentration low enough to permit nitrogenase to function but high enough for it to be able to provide the bacteria with oxygen for respiration.

Legumes do not automatically have the association with *Rhizobium* bacteria, and newly germinated plants use chemical signals to stimulate production of a chemical to instigate nodule formation.[ii] Different legume species form symbiotic relationships with different *Rhizobium* species.

Industrial nitrogen fixation for fertiliser manufacture is also energy-intensive involving high temperatures and pressure. Modern production facilities use natural gas as an energy source, and these need 34GJ/tonne of nitrogen fixed (equivalent 5.6 barrels of oil or 9.52MWh).[iii]

Fixing nitrogen by whatever means requires a lot of energy. Biological nitrogen fixation has the advantage of being solar powered, so does not contribute to global warming or fossil fuel depletion.

It might not work, but it will cost a lot of money

GM nitrogen fixing cereals will be very expensive to develop and will have very long lead time (30-40 years according to one scientist in the field[iv]). There is no guarantee of success. GM nitrogen fixing may prove impossible because it involves making two organisms (a crop plant and the nitrogen fixing bacterium) to work symbiotically by genetically modifying both. This has not evolved in grasses in natural ecosystems, from which our cereal crops were developed.

To date genetic modification has only achieved single gene changes to crop plants, such as disease resistance, herbicide tolerance, insect resistance, or stacked combinations of these. More complicated genetic changes that require multiple gene insertions, such as salt tolerance in plants, have proved much more difficult. No successful GM has involved getting two separate species to work symbiotically.

Research into GM and nitrogen fixation is a meal ticket for the scientists. GM researchers can always claim to be tantalisingly close to a breakthrough in order to secure additional funding. This diverts large sums of research funding into wishful research when it should be used to better effect elsewhere, for instance developing agronomic systems that naturally build soil fertility under the highly variable conditions in which the world's farmers operate.

Why nitrogen fixing may fail using GM

The conversion of nitrogen to ammonia is energy intensive (see box above).

Peas use seventeen grams of carbon from sugars to fix one gram of nitrogen.[v] The carbon is supplied by the plant, so in cereals this would divert energy from growth and grain formation.

The rate of nitrogen fixation is regulated by the bacteria, which ensure that only the required amount of nitrogen is fixed to avoid overloading the plant's metabolism, and the plant, which controls the number of nodules produced. These metabolic processes are controlled by several genes from the plant and the bacterium.

To enable cereals like maize or wheat to be genetically modified to fix nitrogen all these processes have to work as they do in legumes. Such complex outcomes have so far eluded researchers, raising serious doubts about the feasibility of achieving nitrogen fixation in non-leguminous crops. Even if GM nitrogen fixation is successful in cereals it is likely to result in yield reductions because of the demands it would place of the plant's energy resources.

Nitrogen fixing crops already work

Alternative strategies using legumes to fix atmospheric nitrogen are already effective and can be developed more quickly at less cost than GM. For example the push-pull technique in East Africa, now used by thousands of farmers, has increased maize yields from 1 to 3.5 tonnes/ha. This technique, which includes undersowing maize with nitrogen fixing *Desmodium*, builds up soil fertility, improves soil structure, controls pests and weeds and produces more food.[vi]

Organic and many conventional farmers in industrial countries also use nitrogen fixing crops in rotations to build soil fertility, but the potential of this solar powered nitrogen is not yet fully realised.

GM nitrogen fixing cereal crops encourage unsustainable farming

GM nitrogen fixing cereals could encourage the expansion of intensive monoculture arable farming systems, including shorter and less biodiverse arable rotations. This is exactly the kind of farming system the four-year International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) said needs to change (see box).[vii]

GM crops are usually grown in monocultures. Monocultures increase susceptibility to pests and diseases, leading to reliance on chemical controls, which in turn encourage shifts towards more problematic weeds that are more difficult to eradicate and further increases in chemical applications in what is often called the chemical treadmill. In US GM crops this has resulted in overall increases in the amount of chemical herbicides used[viii] – a direct contradiction of GM industry promises to reduce chemical use. In North and South America Roundup Ready GM crops are creating the ideal conditions for weeds to develop resistance to glyphosate because the herbicide has been repeatedly used over many growing seasons. This is leading to significant increases in the use of other weedkillers in an attempt to control them.[ix]

Rotations are a necessary part of good farming practice that build soil fertility and control weeds, pests and diseases. Rotations also help manage nitrogen levels in soils for subsequent crops to use. The greater the diversity of crops and the longer the rotation, the greater the stability and resilience of the farming systems. Nitrogen fixing cereals may tempt farmers into abandoning rotations or shortening them so they become less effective in delivering these other objectives.

GM only deals with one essential plant nutrient

Even if GM nitrogen fixing can be made to work, it will not address the lack of other essential plant nutrients in the soil, such as phosphates and the trace minerals, which impede crop growth and affect the quality of the harvested crop. Many African soils are deficient in phosphates.[x] The price of phosphate fertilisers has risen steeply in recent years, and they are beyond the means of many African farmers, so building soil fertility has to be a higher priority than partial GM technical fixes. Yields from trials show the genetic potential of non-GM cereals could nearly double yields if soil and other conditions are optimised.[xi] In-field conditions are rarely optimal, due to biotic and abiotic factors like disease and weather, but improving the condition, stability, fertility of the soil, and improving the soil's water holding capacity through the addition of organic materials improves growing conditions and reduces the risk of soil erosion. GM can't do this.

No consultation with farmers

Global charities and scientific research institutions rarely ask African farmers about their priorities or what direction they want agricultural research and development to take. African farmers have not been involved in setting the Gates Foundation's agenda for the continent, although many would like to be included.[xii] The Gates Foundation GM nitrogen fixing cereals project is a classic example of the top-down approach that has failed so many times in the past. The Gates Foundation is currently funding £163 million worth of subsidies for artificial fertilisers for small farmers in Africa without carry out any risk assessment on nitrate pollution.[xiii]

People, their knowledge and skills are a major asset, and research and development should build on this rather than impose technical fix approaches that may fail.

GM nitrogen fixing cereals may require soil inoculums

As explained above, different legume species have evolved symbiotic relationships with different nitrogen fixing organisms, with each legume working with a specific species of nitrogen fixing bacterium. Nitrogen fixing can often be improved if the right bacterium is added to the soil as inoculums.[xiv] Nitrogen fixing cereals would need to get this relationship correct if it is to work, and inoculums may be required in many soils.

Nitrogen as planetary pollutant

There is no shortage of nitrogen in the world. Humans use it incredibly inefficiently, to the extent that poorly controlled gaseous and liquid discharges breach planetary limits for managing pollution of freshwater, marine ecosystems and the atmosphere.[xv]

Serious pollution occurs in a number of ways:

- Nitrate fertilisers are not completely taken up by plants.
- Nitrogen can quickly be leached from the soil into groundwater or rivers causing freshwater and marine pollution.
- Nitrate fertiliser can be lost from the soil as nitrous oxide, a powerful greenhouse gas, through the action of denitryfing bacteria when anaerobic conditions exist in the soil.
- Much of the nitrate that is successfully taken up by plants, from whatever source, ends up

being excreted by humans and farm animals and then managed in a way that drains nitrogen away from agricultural ecosystems instead of recycling it.

Human sewage is discharged into rivers and seas either by sewage treatment works or directly without treatment. Sewage treatment is a biological process that mineralises nitrogen as nitrate to avoid high levels of ammonia. It lowers biochemical oxygen demand in effluents, which would kill most aquatic life in receiving waterways. Raw sewage entering rivers or seas undergoes a similar biological process but at greater cost to the environment. Sewage effluent can then lead to eutrophication of rivers – when excessive plant nutrients (mainly nitrates and phosphates) are present due to low flow or lack of dilution, plants (especially algae blooms) proliferate. This causes de-oxygenation of the water as the algal blooms, stimulated by the excess of nutrients, die off and decay, removing oxygen from the water causing the loss of most freshwater life. In marine ecosystems the same thing can occur, and an example of this are the dead spots in the Baltic Sea[xvi] and Gulf of Mexico.[xvii]

Nitrogen fixing cereals will not tackle nitrogen pollution from sewage or animal wastes, nor will it entirely remove the need for artificial nitrate to increase yields. Developing systems for capturing nitrogen in waste and returning it to soil in a form that can enhance plant growth and soil quality with minimal pollution should be the priority and is easily achieved.

Nitrogen fixing crops can also cause pollution

If timing of cultivation is poor, nitrogen fixing crops can also result in nitrogen losses either through leaching[xviii] or the emission of ammonia and nitrous oxide into the air.[xix] Leaching can occur as the vegetation decomposes in the soil if there is no crop present to take up the nitrates produced by soil microbial activity. The correct balance of soil microbes is critical in ensuring that the nitrogen fixed is available to plants as nitrates that can be absorbed through roots. Training farmers to maintain and restore the ecosystem of the soil is therefore of paramount importance as it will encourage deeper rooting, healthier crops and make them more resilience to biotic and abiotic stresses, such a pests and droughts.

Relying on old herbicide regimes

Current and foreseeable herbicide regimes use different compounds for different types of plants (eg, monocotyledonous and dicotyledonous crops), or for herbicide resistant GM crops. Integrating the nitrogen fixation system into cereals may cause difficulties if the resultant plants are then sensitive to a wider range of herbicides than parent plants or the nitrogen fixing donor. Genetically modifying herbicide resistance into the plants in addition to nitrogen fixation as a “solution” could also prove difficult in that, for example, glyophosate can reduce nitrogen fixation by bacteria[xx] and encourage pathogen species.[xxi] Glufosinate ammonium, another herbicide used with GM herbicide resistant crops, also inhibits the work of some species of nitrogen fixing bacteria.[xxii]

GM addresses the wrong problem

Proponents of “sustainable intensification” claims we need to increase food supplies by 50-100% by 2050 to feed a growing global population.[xxiii and xxiv] Several questionable assumptions underpin this argument, and one of the biggest is that we need to produce more food per hectare.

Instead of trying to increase the amount of food produced on a hectare, hunger should be addressed by striving to feed more people per hectare (eg, through multi-cropping to produce more food per hectare). This increases the numbers of possible options, including eating more vegetable protein, reducing food waste, feeding less of our protein crops to livestock and poultry, integrating livestock and poultry into mixed farming systems, localising production systems and maximising the recovery and recycling of organic materials back into the soil.

Another underlying assumption behind “sustainable intensification” is that genetics hold the key to increasing cereal production, despite failing to achieve maximum yields from modern traditionally-bred wheat varieties. Crop genetics, agronomy and soil management need to work together to achieve better yields, so the need for GM nitrogen fixing cereals is unproven.

Weather will always be a major limiting factor on production in any one season, but this can be addressed by multi-variety planting, multi-cropping and greater use of perennial and tree crops (for instance in agro-forestry systems). These are proven techniques with a far higher success rate than speculative investment in technical fixes like GM nitrogen fixation.

Agriculture at a crossroads

The key message of the 2009 International Assessment of Agricultural Knowledge, Science and Technology for Development was:

> *"The way the world grows its food will have to change radically to better serve the poor and hungry if the world is to cope with a growing population and climate change while avoiding social breakdown and environmental collapse."*

The IAASTD calls for a fundamental shift in the use of agricultural knowledge, science and technology (AKST) to successfully meet development and sustainability objectives.

Such a shift should emphasize the importance of the multi-functionality of agriculture, accounting for the complexity of agricultural systems within diverse social and ecological contexts and recognizing farming communities, farm households, and farmers as producers and managers of ecosystems. Innovative institutional and organizational arrangements to promote an integrated approach to the development and deployment of AKST are also needed. Incentives along the value chain should internalize as many negative externalities as possible to account for the full cost of agricultural production to society. Policy and institutional changes should focus on those least served in the current AKST approaches, including resource poor farmers, women and ethnic minorities. Finally the IAASTD emphasizes that small-scale farms across diverse ecosystems need realistic opportunities to increase productivity and access markets.[xxv]

11 better ways to spend US$10 million

1. Integrate nitrogen fixing crops into existing and redesigned rotations.
2. Integrate livestock and crop production to maximise the use and value of animal wastes.
3. Develop safer sewage treatment systems that reduce pollution of valuable water supplies.
4. Develop phosphate and nitrate recovery from existing water-borne sewage treatment systems so they can be recycled back into agricultural soils.
5. Design improved food storage and transport systems and infrastructure to minimise waste.
6. Implement agricultural extension schemes so farmers can access and implement knowledge that will enable them to farm more sustainably.
7. Involve farmers in developing research programmes that meet their needs.
8. Design farming systems to keep pests and pathogens at acceptable levels by concentrating on diverse cropping systems and diversity of varieties instead of continuing to rely on inherently flawed monocultures.
9. Improve protein crops through non-GM modern plant breeding techniques, such as Marker Assisted Selection.
10. Continue to develop water-efficient irrigation techniques that protect soil from salination and safeguarding water supplies.
11. Improve techniques for water harvesting and inter-seasonal storage to minimise evaporation losses.

Notes

[i] Bill and Melinda Gates Foundation, 2012. "John Innes Centre"
[ii] Prome JC, 1999. "Nod Factors, Chemical Signal Exchange Between Bacteria and Leguminous Plants in Nitrogen Fixing Symbiosis". *Annales Pharmacetique Francaises* 57:240-245
[iii] Dawson CJ and Hilton J, 2011. "Fertiliser Availability in a Resource-limited World: Production and recycling of nitrogen and phosphorus. Food Policy". doi:10.1016/j.foodpol.2010.11.012
[iv] *The Economist*, 24 February 2011. "A special report on food: Enough to go round?"
[v] Mahon JD, 1977. "Energy requirement for nitrogen fixation". *Plant Physiology* 60: 817-821

[vi] African Insect Science for Food and Health. Push-Pull: A novel farming system for ending hunger and poverty in sub-Saharan Africa
[vii] International Assessment of Agricultural Knowledge, Science and Technology for Development. Agriculture at a Crossroads . Synthesis Report. A Synthesis of the Global and Sub-Global IAASTD Reports, 2009 http://www.agassessment.org/reports/IAASTD/EN/Agriculture%20at%20a%20Crossroads_Synthesis%20Report%20(English).pdf
[viii] Benbrook C, 2009. "Impacts of genetically engineered crops on pesticide use in the United States: the first thirteen years". The Organic Center
[ix] GM Freeze, 19 October 2011. *Weed resistance in RR crops – An update*
[x] FAO. "Phosphorus Management with Special Reference to Forage Legumes in sub-Saharan Africa"
[xi] *Farmers Weekly*, 15 February 2012. "Winning with wheat: Meeting the challenge of growing record-breaking crops**".** Conventionally-bred wheat varieties are capable of much higher yields than the UK average (around 8 tonnes/ha). A yield of over 15 tonnes/ha was recorded in the UK in 2011, just behind the world record of 15.637 tonnes/ha in New Zealand in 2010. This is currently achieved using high inputs of artificial fertilisers, pesticides and, in some cases, irrigation.
[xii] Pimbert M, Barry B, Berson A and Tran-Thanh K. "Democratising Agricultural Research for Food Sovereignty in West Africa". IIED, CNOP, Centre Djoliba, IRPAD, Kene Conseils, URTEL, Bamako and London
[xiii] GM Freeze, 31 October 2011. *The Bill and Melinda Gates Foundation, Biotechnology and Intensive Farming*
[xiv] Erker B and Brick MA, 2006. "Legume Seed Inoculates". Fact Sheet 0.305. Colorado State University Extension.
[xv] Rockström, J, Steffen W, Noone K, Persson A, Chapin FS, Lambin E, Lenton TM, Scheffer M, Folke C, Schellnhuber H, Nykvist B, De Wit CA, Hughes T, van der Leeuw S, Rodhe H, Sörlin S, Snyder PK, Costanza R, Svedin U, Falkenmark M, Karlberg L, Corell RW, Fabry VJ, Hansen J, Walker B, Liverman D, Richardson K, Crutzen P and Foley J, 2009. "Planetary Boundaries: Exploring the safe operating space for humanity". *Ecology and Society* 14: 32
[xvi] *Ibid*
[xvii] Rabalais NN, Turner RE and Wiseman Jnr WJ, 2002. "Gulf of Mexico Hypoxia, aka 'The Dead Zone'". *Annual Review of Ecology and Systematics*, 33: 235-263
[xviii] Fowler CJE, Condron LM and McLenaghen RD, 2004. "Effects of Green Manures on Nitrogen Loss and Availability in an Organic Cropping System". *New Zealand Journal of Agricultural Research*, 47, 95-100
[xix] Janzen HH and McGinn SM, 1991. "Volatile Loss of Nitrogen During Decomposition of Legume Green Manure". *Soil Biology and Biochemistry* 23:291-297
[xx] Kremer RJ and Means NE, 2009. "Glyphosate and Glyphosate-resistant Crop Interactions with Rhizosphere Microorganisms". *European Journal of Agronomy* 31: 153-161
[xxi] Johal GS and Huber DM. 2009. "Glyphosate Effect on Plant Diseases". *European Journal of Agronomy* 31: 144-152
[xxii] Kriete G, and Broer I1996. "Influence of the Herbicide Phosphinothricin on Growth and Nodulation Capacity of *Rhizobium meliloti*". *Applied Microbiological Biotechnology* 46(5-6):580-586
[xxiii] Royal Society, 2009. *Reaping the Benefits: Science and sustainable intensification of global agriculture*
[xxiv] Foresight Panel, 2011. *Future of Food and Farming: Challenges and choices for global sustainability*
[xxv] *Ibid*