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Review

Involvement of biotechnology in climate change adaptation and mitigation: Improving agricultural yield and food security

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In the context of climate change adaptation and mitigation, biotechnology can respond positively towards reducing vulnerability of natural and human systems to climate change effects. This paper reviews different approaches in which both conventional and modern biotechnology can be employed to address climate change adaptation and mitigation for improved crops adaptability, productivity and food security and contributing to the reduction of the greenhouse gases. The current challenges and future perspectives of biotechnology for climate change adaptation and mitigation are highlighted. The negative effects of climate change on agricultural productivity and food security as a result of extreme temperature, drought, salinity and infectious disease vectors include low yield, hunger and malnutrition. Conventional agricultural biotechnology methods such as energy-efficient farming, use of biofertilizers, tissue culture and breeding for adaptive varieties are among feasible options that could positively address the potential negative effects of climate change and thereby contributing to carbon sequestration initiatives. On the other hand, the adoption of modern biotechnology through the use of genetically modified stress-tolerant, energy-efficient and high-yielding transgenic crops also stand to substantially counter the negative effects of climate change. Safe application of biotechnology will greatly complement other on-going measures being taken to improve agricultural productivity and food security. Both conventional and modern agricultural biotechnologies will significantly contribute to the current and future worldwide climate change adaptation and mitigation efforts.

Key words: Adaptation, carbon sequestration, climate change, green biotechnology, marker assisted selection, mitigation.

INTRODUCTION

Climate change is a significant and lasting change in the statistical properties of the climatic system when considered over long periods of time. It can be caused either by the Earth's natural forces, which include solar radiation and continental drift, or human activities (Theodore, 2001). Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth’s surface, the atmosphere and clouds (IPCC, 2007). Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth’s atmosphere. Moreover, there are a number of entirely man-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine and bromine containing substances. Beside CO_2, N_2O and CH_4, the Kyoto Protocol (http://kyotoprotocol.com) deals with the greenhouse gases such as sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

An increase in the concentration of greenhouse gases leads to increased infrared opacity of the atmosphere, an imbalance that can only be compensated for by an increase in the temperature of the surface-troposphere system. This phenomenon is termed the greenhouse effect (IPCC, 2007).

Adaptation to climate change is a response that seeks to reduce the vulnerability of natural and human systems to climate change effects (IPCC, 2007). Another policy response to climate change is known as climate change mitigation. It refers to human intervention to reduce the sources or decrease intensity of negative climate change effects. Most often, climate change mitigation scenarios involve reductions in the concentrations of greenhouse gases, either by reducing their sources or by increasing their ‘sinks’. Examples of mitigation measures include using fossil fuels more efficiently for industrial processes or electricity generation, switching from biomass to renewable energy, improving the insulation of buildings, and expanding forest and other ‘sinks’ to remove more carbon dioxide from the atmosphere (IPCC, 2007; Sallema and Mtui, 2008). The decline of crops yield, heat stress and ocean acidification are among some of the negative effects of climate change. In order to feed the ever increasing world population, there is a need to double the rate of agricultural production. Biotechnology can contribute positively by mitigating the impact of climate change through green house gas reduction, crops adaptation and increase in yield using less land (Treasury, 2009). This paper seeks to address the contribution of biotechnology to adaptation and mitigation of negative climatic effects.

AGRICULTURAL BIOTECHNOLOGY

Agricultural biotechnology involves the practical application of biological organisms, or their sub-cellular components in agriculture. The techniques currently in use include tissue culture, conventional breeding, molecular marker-assisted breeding and genetic engineering. Tissue culture is the cultivation of plant cells or tissues on specifically formulated nutrient media. Under optimal conditions, a whole plant can be regenerated from a single cell; a rapid and essential tool for mass propagation and production of disease-free plants (Kumar and Naidu, 2006). Advances in breeding help agriculture achieve higher yields and meet the needs of expanding population with limited land and water resources. As a result of improved plant breeding techniques, the productivity gains in worldwide production of primary crops, including maize, wheat, rice and oilseed has increased by 21% percent since 1995, while total land devoted to these crops has increased by only 2% (Treasury, 2009). In molecular assisted breeding, molecular markers (identifiable DNA sequences found at specific location of the genome) are being used. By determining location and likely actions of genes, scientists can quickly and accurately identify plants carrying desirable characteristics, hence conventional breeding can be conducted with greater precision (Mneney et al., 2001; Sharma et al., 2002). Molecular markers can be used in plant breeding to increase the speed and efficiency of the introduction of new genes (marker assisted introgression), understanding of genetic diversity, taxonomic relationships between plant species and biological processes such as mating systems, pollen or disease dispersal (Johanson and Ives, 2001). Biotechnology enables development of disease diagnostic kits for use in laboratory and field. These kits are able to detect plant diseases early, by testing for the presence of pathogen’s deoxyribonucleic acid (DNA) or proteins which are produced by pathogens or plants during infection (Kumar and Naidu, 2006). Conventional agricultural biotechnologies works better when combined with modern biotechnological approaches.

Modern agricultural biotechnology refers to biotechnological techniques for the manipulation of genetic material and the fusion of cells beyond normal breeding barriers. The most obvious example is genetic engineering to create genetically modified organisms (GMOs) through ‘transgenic’ technology involving the insertion or deletion of genes. In genetic engineering or genetic transformation, the genetic material is modified by artificial means. It involves isolation and cutting of a gene at a precise location by using specific enzymes. Selected DNA fragments can then be transferred into the cells of the target organism. The common practice in genetic engineering is the use of a bacterium *Agrobacterium tumafaciens* as a vector to transfer the genetic trait (Johanson and Ives, 2001). A more recent technology is ballistic impregnation method whereby a DNA is attached to a minute gold or tungsten particle and then ‘fired’ into the plant tissue (Morris, 2011). Crops may be modified for improved flavour, increased resistance to pests and diseases, or enhanced growth in adverse weather conditions. In recent years, biosafety and genetic engineering projects have been initiated in Africa, with the aim of introducing genetically modified organisms into Africa’s agricultural systems. Already, countries like South Africa, Egypt and Burkina Faso have commercialized GMOs while many others have developed the capacity to conduct research and development in modern agricultural biotechnology (Mayet, 2007). ‘Green biotechnology’ is the term referring to the use of environmentally friendly solutions in agriculture, horticulture, and animal breeding processes (Treasury, 2009).

Recombinant DNA technology has significantly augmented the conventional crop improvement, and has the potential to assist plant breeders to meet the increased food demand predicted for the 21st century. Dramatic progress has been made over the past two decades in manipulating genes from diverse and exotic sources, and inserting them into microorganisms and crops to confer resistance to pests and diseases, tolerance to herbicides, drought, soil salinity and aluminium toxicity, improve post-harvest quality, enhance nutrient uptake and nutritional quality; increase photosynthetic rate, sugar and starch production, increase effectiveness of bio control agents, improve understanding of gene action and metabolic pathways, and production of drugs and vaccines in crops (Sharma et al., 2002 ; Vallad and Goodman, 2004).

BIOTECHNOLOGY FOR CLIMATE CHANGE MITIGATION

Greenhouse gas reduction

Agricultural practices such as deforestation, inorganic fertilizer use and overgrazing currently account for about 25% of green house gases (CO_2, CH_4 and N_2O) emission (Treasury, 2009). Various initiatives under the banner of green biotechnology, may offer solution to decrease green house gases and mitigate climate change by giving farmers opportunities to use less and environmentally friendly energy, carbon sequestration and reduce fertilizer usage (Treasury, 2009).

Use of environmentally friendly fuels

Given the impacts of climate change on agricultural productivity and the role played by agriculture practices in global warming, agricultural techniques must play a crucial role in the fight against climate change. Production of biofuels, both from traditional and GMO crops such as sugarcane, oilseed, rapeseed, and jatropha will help to reduce the adverse effects of CO_2 emission by the transport sector (Sarin et al., 2007; Treasury, 2009). Energy efficient farming will therefore adopt machines that use bioethanol and biodiesel instead of the conventional fossil fuels. Green energy programs through plantations of perennial non edible oil-seed producing plants will help in cleansing the atmosphere and production of biodiesel for direct use in the energy sector, or in blending biofuels with fossil fuels in certain proportions thereby minimizing use of fossil fuels to some extent (Lua et al., 2009; Jain and Sharma, 2010; Lybbert and Summer, 2010).

Less fuel consumptions

Organic farming uses less fuel by the application of compost and mulching techniques which reduce weeds and herbicides spraying due to less ploughing (Maeder et al., 2002). Reduced irrigation would also contribute to reduced fuel usage, thereby reducing the amount of CO_2 release into the atmosphere. Using modern biotechnology such as GMOs and other related technologies facilitate less fuel usage by decreasing necessity and frequency of spraying and reducing tillage or excluding the tillage practice. For example, insect-resistant GM crops reduce fuel usage and CO_2 production by reducing insecticides application.

Reduction of fuel usage due to the application of biotechnology amounted to savings of about 962 million kg of CO_2 emitted in 2005, while the adoption of reduced tillage or no tillage practices led to a reduction of 40.43 kg/ha or 89.44 kg/ha CO_2 emissions due to less fuel usage respectively (Brookes and Barfoot, 2006, 2008).

Carbon sequestration

The capture or uptake of carbon containing substances, in particular carbon dioxide (CO_2), is often called carbon sequestration. It is commonly used to describe any increase in soil organic carbon content caused by change of land management, with implication that the increased soil carbon storage mitigates climate change (Powlson et al., 2011). Therefore, soil carbon sequestration is an important strategy to mitigate the increase of atmospheric CO_2 concentration. Reducing the amount of conventional tillage is one way of enhancing carbon sequestration. By leaving at least 30% of residue on the soil surface, no-till agriculture reduces loss of CO_2 from agricultural systems and may also play a role in reducing water loss through evaporation, increase soil stability and creation of cooler soil microclimate. Conservation practices that help prevent soil erosion, may also sequester soil carbon and enhance methane (CH_4) consumption (West and Post, 2002; Johnsona et al., 2007). Powlson et al. (2011) have suggested that the climate change benefit of increased soil organic carbon from enhanced crop growth (for example using industrial fertilizers) must be balanced against greenhouse gas emissions emanating from the manufacture and use of such fertilizers.

In modern agricultural practices, genetically modified Round up Ready ^{TM} (herbicide resistant) soybean technology has accounted for up to 95% of no-till area in the United States of America (USA) and Argentina, and led to sequestration of 63,859 million tones of CO_2 (Fawcett and Towery, 2003; Brimner et al., 2004; Kleter et al., 2008). The modified crops reduce the need for tillage or ploughing to allow farmers to adopt ‘no till’ farming practices. In terms of climate change mitigation, this practice enhances soil quality and retails more carbon in the soil (Brookes and Barfoot, 2008).

Reduced artificial fertilizer use

The dependency on agricultural chemicals to sustain productivity in marginal landscapes has led to a global-scale contamination of the environment with toxins that change the course of biogeochemical cycles (Ogunseitan, 2003). Reduced fertilizer use also means less nitrogen pollution of ground and surface waters. Artificial inorganic nitrogenous fertilizers such as ammonium sulphate, ammonium chloride, ammonium phosphates, sodium nitrate and calcium nitrate are responsible for the formation and release of greenhouse gases (particularly N_2O) from the soil to the atmosphere when they interact with common soil bacteria (Brookes and Barfoot, 2009). To reduce the negative effects of artificial fertilizers, the use of environmentally friendly biotechnology-based fertilizes are being encouraged.

Biofertilizers

Organic farming technologies utilizing bio-based fertilizers (composted humus and animal manure), or crop rotation and intercropping with leguminous plants with nitrogen-fixing abilities are some of the conventional biotechnological options for reducing artificial fertilizer use. In modern biotechnology, the use of mutation or genetic engineering techniques to improve *Rhizobium* inoculants have resulted to strains with improved nitrogen-fixing characteristics (Zahran, 2001). Biotechnological advances involving the induction of nodular structures on the roots of cereal crops such as rice and wheat offer a bright prospect of non-leguminous plants being enabled to fix nitrogen in the soil (Kennedy and Tchan, 1992; Paau, 2002; Saikia and Jain, 2007; Yan et al., 2008). Another option is the cultivation of GM crops that use nitrogen more efficiently. An example of such crops is the nitrogen-efficient GM canola which not only reduces the amount of nitrogen fertilizer that is lost into the atmosphere or leached into soil and waterways, but it also impacts positively on the economies of farmers through improved profitability (Treasury, 2009). Managing soil nitrogen to match crop needs can reduce N_2O emission and avoid adverse impacts on water quality. Also, manipulating animal diet and manure management can reduce CH_4 and N_2O emission from animal husbandry (Johnsona et al., 2007).

BIOTECHNOLOGY FOR CROP ADAPTATION

Climate change leads in reduced crop yield due to inadequate rainfall, emergence of potential weeds, pests and diseases caused by fungi, bacteria and viruses (Johnsona et al., 2007; Lin et al., 2008). One way of adapting to such calamities is to apply agricultural biotechnologies that counter the effects of such changes by improving crop productivities per unit area of land cultivated.

Biotechnology for increased yield per unit area of land

To satisfy the growing worldwide demand for food crops, two options are available: Either to increase the area under production, or improve productivity on existing farmland (Edgerton, 2009). Given the world's available arable land, and the climate change dynamics, the second option is more feasible. Utilizing organic residues as a source of nutrients for plants, good agronomical practices such as landscape management, crop rotation or mixed farming, and use of traditional and indigenous knowledge on 'non-chemical' pests and diseases control are some of conventional options (Bianchi et al., 2006). Biotechnology and application of advanced techniques in breeding can help agriculture further to achieve higher yields and meet needs of expanding population with limited land and water resources (Treasury, 2009).

Adaptation to biotic stresses

The major aim of agricultural biotechnology is to enhance productivity and maximize productive capacity of diminishing resources. Conventional landscape management practices and breeding initiatives have contributed significantly to crop adaptations through the development of strains that are resistant to biotic stresses such as insects, fungi, bacteria and viruses (Valllad and Goodman, 2004; Bianchi et al., 2006). In modern biotechnology, the ability of a soil bacterium (*Baccilus thuringiensis, Bt*) gene to be transformed into maize, cotton and other crops to impart internal protection against insects (mainly of the order lepidoptera and diptera) significantly contributes to agricultural pest control strategies. For many farmers, *Bt* crops are proving to be valuable tools for integrated pest management programs by giving farmers new pest control choices (Zhe and Mithcell, 2011). Transgenic canola (oil seed rape) and soybean have been modified to be resistant to specific herbicides (May et al., 2005; Bonny, 2008). Also, GM cassava, potatoes, bananas and other crops that are resistant to fungi, bacteria and viruses are in development; some have already been commercialised while others are undergoing field trials (Mneney, 2001; Van Camp, 2005). Studies carried out between 2002 and 2005 found out that biotic stress-resistant GM crops account for increases in average yield of 11 to 12% for canola and maize compared to conventional crops (Qaim and Zilberman, 2003; Gomez-Barbero et al., 2008; Brookes and Barfoot, 2008, 2009).

Adaptation to abiotic stresses

Climate change poses an enormous challenge in terms of available agricultural land and fresh water use. Abiotic stresses including salinity, drought, extreme temperatures, chemical toxicity and oxidative stress have negative impacts on agriculture and natural status of the environment. The agricultural sector uses about 70% of the available fresh water and this is likely to increase as temperature rises (Brookes and Barfoot, 2008). Moreover, about 25 million acres of land is lost each year due to salinity caused by unsustainable irrigation techniques (Ruane et al., 2008). It is anticipated that increased salinity of arable land will lead to 30% land loss within 25 years and up to 50% by the year 2050 (Wang et al., 2003; Valliyodan et al., 2006). Therefore, solutions to facilitate crop adaptation to abiotic stressful conditions (drought and salinity) need to be developed. Plant biotechnology programs should give priority to the breeding for drought and salinity tolerance in crops and forests. Conventional approaches to mitigate the effects of drought and salinity stresses involve selection and growing drought resistant crops that can tolerate harsh conditions on marginal lands. Such crops include cassava, millet and sunflower (Manavalan et al., 2009). While mulching to prevent surface water loss has been a common practice for organic farmers; tissue culture and breeding are being used to cross drought tolerant crops with other high yielding species to create a drought tolerant, high yielding hybrids (Apse and Blumwald, 2002; Ruane et al., 2008). However, although adaptation to stress under natural conditions has some ecological advantages, the metabolic and energy costs may overshadow its benefit to agriculture. Therefore, blending traditional and molecular breeding techniques would be most desirable (Wang et al, 2001; Apse and Blumwald, 2002).

Molecular control mechanisms for abiotic stress tolerance are based on activation and regulation of specific stress-related genes. Transgenic plants are engineered based on different stress mechanisms: metabolism, regulatory controls, ion transport, antioxidants and detoxification, late embryogenesis abundance, heat shock processes and heat proteins (Wang et al., 2001, 2003). It has been reported by Zhu (2001) that salt tolerant plants also often tolerate other stresses including chilling, freezing heat and drought. Already, a number of abiotic stress tolerant, high performance GM crop plants have been developed. These include tobacco (Hong et al., 2000); *Arabinopsis thaliana* and *Brasicca napus* (Jaglo et al., 2001); Tomato (Hsieh et al., 2002; Zhang and Blumwald, 2002); rice (Yamanouchi et al., 2002); maize, cotton, wheat and oilseed rape (Yamaguchi and Blumwals, 2005; Brookes and Barfoot, 2006). Plants may also be engineered to reduce the levels of poly (ADP ribose) polymerise, a key stress related enzyme, resulting in plants that are able to survive drought compared to their non-GM counterparts. Field trial results have shown a 44% increase in yield in favour of such GM crop plants (Brookes and Barfoot, 2008). Another technology involving the use of genetic ‘switches’ (transcription factors and stress genes) from microbial sources is currently under research by the United Kingdom (UK) Agricultural Biotechnology Council (ABC; http://www.abcinformation.org). This technology has been tested and resulted in two-fold increase in productivity for Arabidopsis and 30% yield increase for maize during severe water stress. It has been suggested that comprehensive breeding plan for abiotic stress should include conventional breeding and germplasm selection, elucidation of specific molecular control mechanisms in tolerant and sensitive genotypes, biotechnology-oriented improvement of selection and breeding procedures (functional analysis, marker probes and transformation with specific genes) and improvement and adaptation of current agricultural practices (Wang et al., 2003). With the availability of whole genome sequences of plants, physical maps, genetics and functional genomics tools, integrated approaches using molecular breeding and genetic engineering offer new opportunities for improving stress resistance (Manavalan et al., 2009).

Agroecology and agroforestry

Consequences of global climate change responsible for altering patterns of temperature and precipitation are threatening agriculture in many tropical regions. Agroecological and agroforest management systems, such as shade management in crop systems, may mitigate the effects of extreme temperature and precipitation, thereby reducing the ecological and economic vulnerability of many rural farmers, and improving the agroecological resistance to extreme climate events (Lin et al., 2008). Fungal applications in biotechnology, termed mycobiotechnology, are part of a larger trend toward using living systems to solve environmental problems and restore degraded ecosystems. The sciences of mycoforestry and mycorestoration are part of an emerging field of research and application for regeneration of degraded forest ecosystems (Cheung and Chang, 2009). Mycorestoration attempts to use fungi to help repair or restore ecologically harmed habitats. Whether the habitats have been damaged from human activities or natural disasters, saprophytic and mycorrhizal fungi can help steer the course to recovery. A number of non-legume woody plants such as casuarinas (*Casuartna* sp.) and alders (*Alnus* sp.) can fix nitrogen symbiotically with actinomycete bacteria (*Frankia* sp.), a phenomenon that is beneficial to forestry and agroforesty (Franche et al., 1998). Both endo- and ectomycorrhizal symbiotic fungi together with actinomycetes have been used as inoculants in regeneration of degraded forests (Saikia and Jain, 2007). Therefore, both mycorrhizal fungi and actinorhizal bacteria technologies can be applied with the aim of increasing soil fertility and improving water uptake by plants (Ruane et al., 2008). Afforestation would indirectly contribute to improved agricultural productivity and food security because forests create microclimates that improve rainfall availability. Furthermore, forests act as carbon sinks thereby contributing towards sequestration and concomitant greenhouse reduction effects for climate change mitigation. Consequently, forestry and agroforestry offer the potential to develop

Table 1. Conventional agricultural biotechnologies for climate change adaptation and mitigation.

Measure	Biotechnology	Application	Reference
Climate change mitigation: Reduced artificial fertilize use	No-till practices	Coffee and banana and horticultural farming	West and Post, 2002; Johnsona et al., 2007; Powlson et al., 2011.
	Biofertilizers	Composting and use of animal manure	Treasury, 2009; Powlson et al., 2011.
Carbon sequestration	Agroforestry	Mycorrhizal and actinorrhizal symbiosis	Franche et al., 1998; Zahran, 2001.
		Afforestation (native & exotic trees)	Lin et al., 2008 .
		Inoculation of nitrogen fixers	Zahran, 2001.
	Biofuels production	Biogas from agro wastes	Treasury, 2009.
		Bioethanol from sugarcane	Lybert and Summer, 2010;
		Biodiesel from jatropha, palm oil	Sarin et al., 2007; Lua, 2009; Jain and Sharma, 2010.
Adaptation to climate change: Adaptation to biotic and abiotic stresses	Mulching	Horticlutural practices	Johnsona et al., 2007.
	Tissue culture	Drought tolerant sorghum, millet, sunflower.	Apse and Blumwald, 2002.
	Cross breeding	Drought resistant Pearl millet	Ruane et al., 2008.
	Agroforestry	Shading coffee and banana plantations.	Franche et al., 1998; Saikia and Jain, 2007.
Improved productivity	Increased crop yield per unit area of land	Crop rotation, traditional pesticides.	Edgerton, 2009; Treasury, 2009.

synergies between efforts to mitigate climate change and efforts to help vulnerable populations to adapt to negative consequences of climate change (Verchot et al., 2007). The conventional and modern biotechnological initiatives related to climate change adaptation and mitigation are summarized in Tables 1 and 2.

CHALLENGES AND FUTURE PERSPECTIVES

As the world population is expected to reach 8 billion people by 2028, the demand for food is also expected to increase by 55%. Moreover, out of world's total land area of 13 billion hectares (ha), only 12% is cultivated. In the next 30 years, developing countries will need an additional 120 million hecters for crops (Ruane et al., 2008). Therefore, science and technology should take a lead in spearheading increased agricultural productivity. If we want to feed the world without destroying our resources, science and technology should drive the development of modern agriculture. Genetically modified crop varieties are the most cost effective ways to sustain farming in marginal areas and restore degraded lands to production (Treasury, 2009). Efforts should be made to integrate local and conventional biotechnologies with modern biotechnology strategies within national policies and legal frameworks in order to increase resilience of local crop varieties against changes in environmental dynamics (Stinger et al., 2009).

Despite the availability of promising research results, many applications of biotechnology have not met their full potential to deliver practical solutions to end-users in developing countries (Ruane et al., 2008). The challenges for the bioenergy sector are concerns about imminent land, water, food and feed conflicts as a result of introduction of large scale plantations of energy crops in limited arable land (Rubin, 2008; Mtui, 2009). In the area of increased soil fertility using biofertilizers, nitrogen fixation research is moving towards genomic studies whereby complete sequences of nitrogen-fixing bacteria are being elucidated (Yan et al., 2008). In forest biotechnology, there is a poor understanding of forest genomics and complex ecosystem processes at landscape scales. It is argued that genomic approaches for monitoring soil microbial communities could become an important tool in understanding the effects of biomass removal for biofuels, or enhancing durable below-ground carbon sequestration (Groover, 2007).

Modern biotechnology has encountered enormous public debates related to risks and benefits of the GMOs

Table 2. Modern agricultural biotechnologies for climate change adaptation and mitigation.

Measure	Biotechnology	Application	Reference
Climate change mitigation:	Engineering herbicide resistance to reduce spraying	GM soy beans GM canola	Fawcett and Towery, 2003; Brimner et al., 2004; Kleter et al., 2008
Less fuel consumption	Engineering insect resistance to reduce spraying	*Bt* maize, cotton, and eggplants	May et al., 2005; Bonny, 2008; Zhe and Mithcell, 2011
Reduced artificial fertilize use	Engineering nitrogen fixation	Genetic improvement of *Rhizobium*; inducing N-fixation to non-legumes	Tchan, 1992; Zahran, 2001; Kennedy and Paau, 2002; Saikia and Jain, 2007; Yan et al., 2008
Carbon sequestration	No-till farming due to Biotechnological advances	Herbicide resistant GM soy beans, canola	Fawcett and Towery, 2003; Kleter et al., 2008
	Green energy	GM energy crops	Lybbert and Summer, 2010
	Nitrogen- efficient GM crops	N-efficient GM canola	Johnsona et al., 2007
Adaptation to climate change:	Molecular marker assisted breeding for stress resistance	Drought resistant maize, wheat hybrids	Wang et al., 2001, 2003
Adaptation to biotic and abiotic stresses	Engineering drought tolerance	GM Arabidopsis , Tobacco, maize, wheat, cotton, soybean	Hong et al., 2000; Jaglo et al., 2001; Yamanouchi et al., 2002; Manavalan et al., 2009
	Engineering salt tolerance	GM tomato, rice	Hsieh et al., 2002; Zhang and Blumwald, 2002
	Engineering heat tolerance	GM Arabidopsis, GM *Brassica* Sp.	Jaglo et al., 2001; Zhu, 2001.
Improved productivity per unit area of land	Increased crop yield per unit area of land	Fungal, bacterial and viral resistant GM cassava, potatoes, bananas, maize, canola.	Mneney, 2001; Van Camp, 2005; Gomez-Barbero et al., 2008

technology in terms of health, environment, socio-economic and ethical issues (Bakshi, 2003). The attitudes and interests of various stakeholder groups supporting or opposing modern biotechnology have led to polarized opinions (Bruinsma et al., 2003; Aerni 2005). There have been opponent activists who dispute the safety of the technology, citing possible risks including: creation of more rigorous pests and pathogens, exacerbating the effects of existing pests, harm to non target species, disruption of biotic communities and loss of species and genetic diversity within species (Snow et al., 2005). Political, socio-economic, cultural and ethical concerns about modern biotechnology are related to the fear of technological “neo-colonialism” in developing countries, intellectual property rights, land ownership, customer choices, negative cultural and religious perceptions, and fear of the unknown (Brink et al., 1998, Makinde et al., 2009). Such public concerns have led to over-regulation of the technology, which threatens to retard its applications (Qaim, 2009). It is suggested that the effects of GMOs should be studied case-by-case, incorporating assessment of potential plant/ecosystem interactions, accessible and relevant indicators and tests for unforeseen effects (Bruinsma et al., 2003). In order to overcome the challenges currently encountered in development and application of modern biotechnology, governments ought to put in place appropriate biosafety and biotechnology policies and legal frameworks before adopting such technologies (Stringer et al., 2009). Table 3 summarizes major challenges to climate change and agricultural biotechnology, and some proposed solutions.

CONCLUSION

This review shows that safe development and application of plant biotechnology can contribute positively towards climate change adaptation and mitigation through reduction of CO_2 emissions, carbon sequestration, reduced fuel use, adoption of environmentally friendly fuels, and reduced artificial fertilizer use, employing biofuels for improved soil fertility and crop adaptability. These measures are meant to improve agricultural productivity and food security, and at the same time protecting our environment from adverse effects of climate change. There is consensus among scientific

Table 3. Challenges in the climate change and biotechnology debates, and proposed solutions.

Challenge	Proposed solution	Reference
Climate change: Scepticism on the cause of climatic variations: whether it is man-made or natural phenomena.	Arguments should be scientifically-driven; not politically or self-interest driven.	Oreskes, 2004; Doran and Zimmerman, 2009; Anderegg et al., 2011
Carbon/emission trading: an industrialized world issue or the whole world initiative?	Each country in the world has a stake in effecting the reduction of CO_2 emissions.	IPCC, 2007; Barker, 2007
Food security: Overall, the world's food security is not stable.	Science and technology should take a leading role to ensure food sufficiency.	Ruane et al., 2008; Treasury, 2009
Biotic and abiotic stresses threaten food productivity.	Conventional and modern biotechnology interventions are needed to solve the problem.	Gomez-Barbero et al., 2008; Manavalan et al., 2009
Renewable energy: There is imminent land, water, food and feed conflicts in large-scale production of energy crops.	Encourage the use of marginal lands; use second generation sources (agricultural and forest residues) for bioenergy.	Mtui 2007, 2009; Rubin, 2008
Modern biotechnology: Safety concerns on health and environment.	Concerns on side effects of GMOs should be science-based, and should be studied case-by-case.	Bakshi, 2003; Bruinsma et al., 2003; Aerni, 2005; Snow et al., 2005
Socio-economic, cultural and ethical concerns such as IPR issues; loss of traditional crops; fear of the unknown.	National biosafety and biotechnology policies and legal frameworks should guide the technologies.	Treasury, 2009, Qaim, 2009.

community that climate variability is a result of direct and indirect anthropogenic activities. An integrated approach to safe applications of both conventional and modern agricultural biotechnologies will not only contribute to increased yield and food security, but it will also significantly contribute to climate change adaptation and mitigation initiatives.

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