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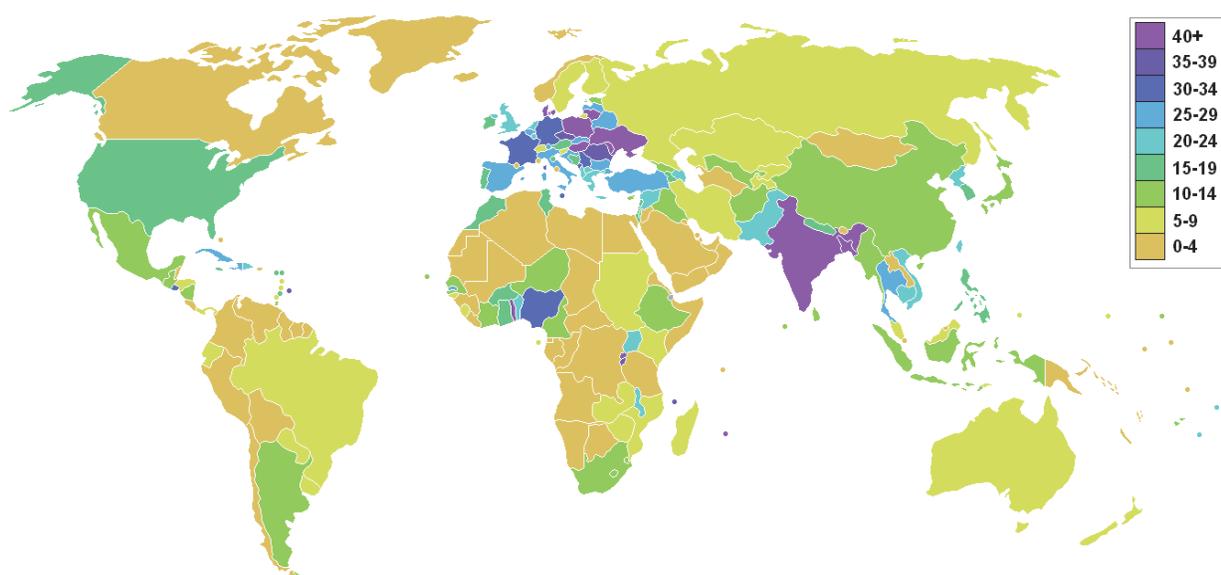


# Innovations in Agricultural Biotechnology in Response to Climate Change

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## 1. Introduction

Food security for all will be a prominent issue for the next century. Today one billion people of the world are undernourished and more than a third are malnourished (Godfray et al., 2010). The chronically hungry have compromised immune systems and succumb to easily preventable infections. As the world's population continues to increase, ensuring that the earth has enough food that is nutritious will be a difficult task enough. However, the looming threat of climate change will exasperate the situation even further. The impact of climate change on the world's food supply is predicted to be far-reaching. At high risk is sub-Saharan Africa, a drought-prone continent with a little under 10% of current land designated to have agricultural potential predicted to turn into desert within the next 50-70 years (Global Hunger Index)(Figure 1).



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Fig. 1. Arable land percentage by country, as listed on CIA factbook, accessed June 2006.

Drought is also anticipated for Asia, as an accumulative result of climate change. Rice crops tend to be vulnerable to lengthy hot, dry seasons. Himalayan glaciers, which feed the rivers and streams of both China and India, are predicted to lose as much as 80 per cent of their volume within the next quarter century (Global Hunger Index). Meanwhile, temperate zones in other parts of the world such as North America and Europe will encounter extreme weather conditions, such as hurricanes and floods. Different patterns of rainfall in a particular habitat will impact the ecosystem of that region, altering biodiversity and changing the growing seasons of particular crop types.

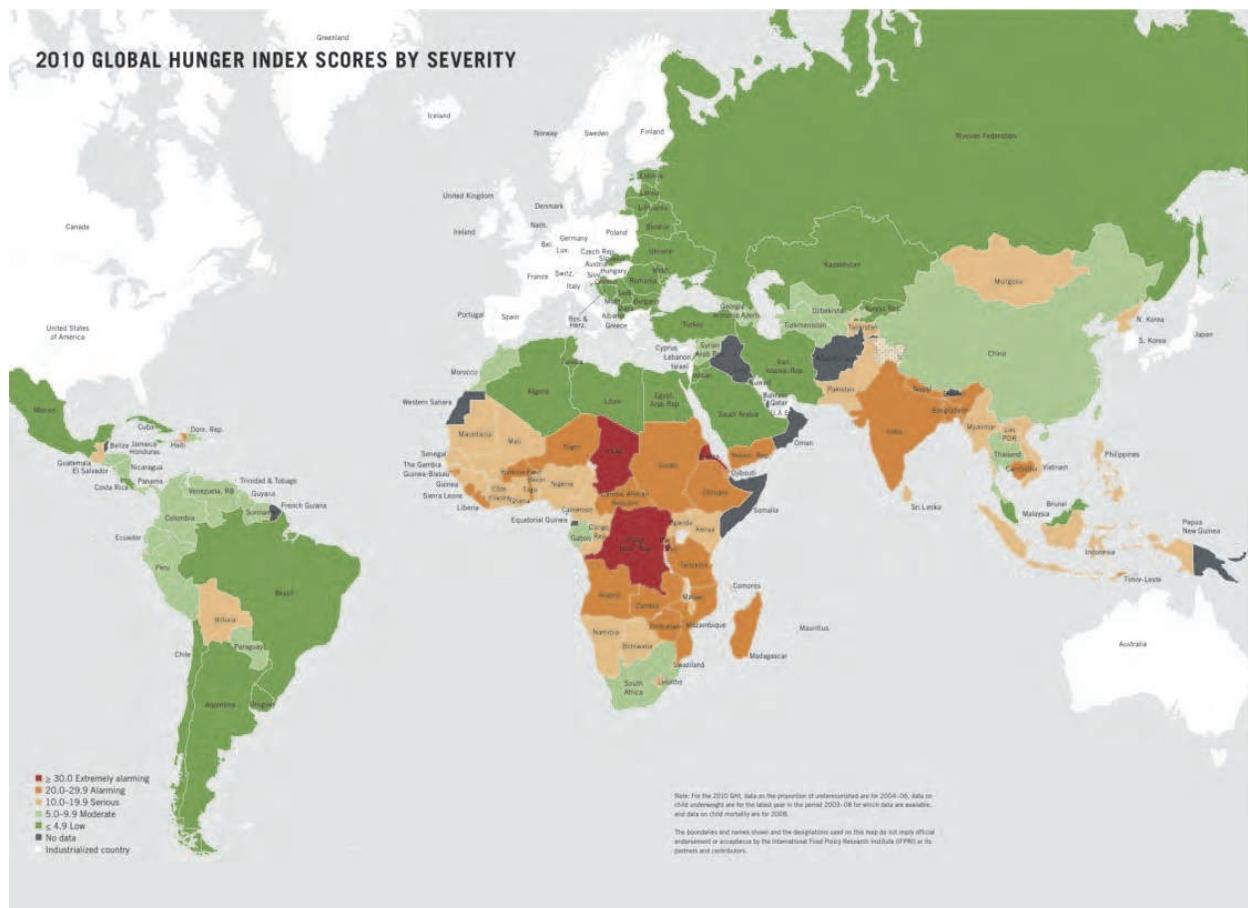
Even without taking the advance of climate change into account, the burgeoning world population will continue to grow to an estimated 9 billion people by 2050 (Ejeta, 2010). Food prices are predicted to continue to fluctuate wildly as the demand for food increases. The situation is confounded even further by a competition for land and water between crops grown for food and crops grown for energy, in the form of first generation biofuels.

In summation, agricultural productivity must clearly improve by significant amounts in order to meet the world's needs and address environmental stresses brought about by climate change. For example, we must change the way we think about the use of fossil fuels as fertilizers for agricultural production. Climate change will also impact water availability, and crops must be designed with this in mind. Even concerns such as pest management will be affected by climate change in ways that are too unpredictable to determine.

## **2. Climate change and food security**

The world's most food insecure often are rural farmers, subsisting on small farms in developing countries (Figure 2). Also falling under the category of the world's poorest, these farmers cannot afford modern irrigation systems or fertilizers and pesticides. As a result, the soil quality of these farms tends to be nutrient exhausted and susceptible to insects and other pests. These facts set the stage for even greater hardships. The world's food requirements are expected to double by 2050 (Barrett, C.B. 2010). At the same time, the total acreage of arable land that could support agricultural use is already near its limits, and may even decrease over the next few years due to salination and desertification patterns resulting from climate change (CIA Factbook). Fresh water available for agricultural use will increasingly become scarce, and changing weather patterns will impact growing conditions. Without radical changes in agricultural practices, the future could not look any more bleak for the world's poor.

There is a silver lining, however, to all of this gloom and doom. Clearly, changing the way we think about crop production must take place on multiple levels. New varieties of crops must be developed which can produce higher crop yields with less water and fewer agricultural inputs. Besides this, the crops themselves must have improved nutritional qualities or become biofortified in order to reduce the chances of 'hidden hunger' resulting from malnourishment. The use of plants to produce therapeutic proteins, for example, will result in affordable medicines which can better address a burgeoning global population. Furthermore, more arable land can be recovered from polluted regions through phytoremediation and related technologies involving the plant sciences. Agricultural technologies currently under development will renovate our world to one that can comfortably address the new directions our planet will take as a result of climate change.



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Fig. 2. Global hunger index scores by severity.

### 3. Sustainable intensification of agriculture and climate change

It is difficult to envision the optimum way to increase crop production using a single uniform strategy. Instead, a variety of approaches must be employed and tailored for any particular agricultural setting. New technologies must be developed to improve crop yield, reduce damage due to pests and minimize food waste, yet also use less land, fertilizer and water. This ‘sustainable intensification’ includes the marriage of conventional plant breeding with plant biotechnology, including genetic modification (GM) to achieve these goals (Timmer, 2003, Christou & Twyman 2004).

The world’s rural poor have much to benefit by the use of agricultural biotechnology. Genetically modified crops are under construction which are nutrient rich and disease resistant. Transgenic crops are being generated which can thrive in poor soils, tolerate extreme conditions such as drought and heat, and accumulate much needed minerals and vitamins in edible plant parts. Other plants can be generated which will extract heavy

metals and pollutants from contaminated soils, providing more arable land. New crops that are designed to be more adaptable to the upcoming ordeals of climate change will make food security far more achievable. The following section describes some of these up-and-coming technologies.

Much attention has been placed on generating crops which are tolerant to heat, drought and other environmental stresses. Plant varieties are required which are capable of surviving and even thriving in a variety of rapidly changing and extreme environmental conditions. Sub-Saharan Africa, for example, a continent already hungry, will face even more heat and desertification. Some regions of Asia, on the other hand, may find high salinity a challenge for crop growth. The methods by which scientists are addressing this challenge are creative to say the least. Plant architecture, for example, can be modified to enable plants to resist adverse environmental conditions. The shape, distribution and consistency of plant roots and leaves can be designed to better catch and retain water in times of extreme drought. Roots can be altered for shallow growth so that they remain close to the surface, the better to collect dew and runoff from precipitation. Similarly, leaves can be modified to trap moisture from escaping by strictly controlling their stomata (pores) (Somvanshi, 2009, Bhatnagar-Mathur *et al.*, 2008, Tester, & Langridge, 2010). Plants with modified photosynthetic machinery can be tailored to be more receptive to changing weather patterns.

As a result of climate change, plants which exhibit tolerance to high salt content in soils will be essential. High salinity currently affects one fifth of irrigated land, resulting at the least in inhibition of crop growth, and at the most, death. Other plant types have developed tactics to respond to high salt conditions; these techniques can be exploited to help today's crops cope with this unique stress. For example, some plants have developed the ability to sequester sodium ions into cell vacuoles or even block sodium ions from entering plant cells. The genes involved in these diverse mechanisms have been identified and have been transferred to crop plants such as rice, which lack these characteristics. Crops modified in this fashion can then thrive in regions which were previously unsuitable for growth (Tuteja, 2007, Uddin *et al.*, 2008).

The requirement of crop plants for nitrogen through the use of fertilizers may also be impacted as a consequence of climate change. In sub-Saharan Africa, for example, access to artificial fertilizers is poor to non-existent. Yet nitrogen continues to be a necessary staple in agriculture for the industrialized world, and causes problems with respect to runoff into waterways or release to the atmosphere in the form of greenhouse gases. A principal concern is the fact that artificial fertilizers are actually produced from fossil fuels, further entwining industrialized countries to petroleum production, and the dependence which lies therein. Crops which are efficient in nitrogen usage and/or have lower nitrogen requirements are much needed. For example, rice crops have been developed which have the ability to uptake nitrogen from the soil with improved efficiency, thus relieving the intense requirement for nitrogen from fertilizers. Since these plants exhibit an improvement in nitrogen uptake, they can achieve a desired biomass and seed yield with a reduced need for high levels of nitrogen application through fertilizers. Other means by which to reduce the requirement for nitrogen is the generation of corn and other crops which can fix their own nitrogen, through the modification of current nitrogen-fixing bacteria ([www.eurekalert.org](http://www.eurekalert.org)). These novel technologies will facilitate crop growth in the absence of fertilizers, and could help those in Africa who have limited access to nitrogen-based fertilizers yet will soon face the greatest environmental impact due to climate change.

Global warming will bring about a change in biodiversity in many of the world's microclimates. Insects and other plant pathogens will eventually bridge gaps in their geographical locations and host ranges as never before. As a result, the introduction of both old and new plant pests will bring about a change in management strategies. Just as the prospect of global warming is predicted to bring about increases in mosquito production, and most likely increases in vigorously fought deadly diseases such as malaria and Dengue fever, plant pathogens will also most likely make an appearance in plant hosts where they were unable to gain an advantage before. Plant pathologists will be required to be ever more vigilant in their surveillance of newly emerging epidemics caused by plant pathogens as a result of global warming. The spruce budworm for example, in the boreal forests of North America, has been able to take advantage of the warmer summers and longer growing seasons to reproduce more rapidly each year, resulting in deadly forest infestations. These infestations affect both the natural ecosystems of the forests themselves, as well as the lumber industry, a prime economic engine of the area ([canadaforests.nrcan.gc.ca](http://canadaforests.nrcan.gc.ca)). New disease resistant plants will be required by incorporating molecular breeding strategies with genetic modification. Many crop plants have now been engineered which utilize a number of novel techniques to exhibit resistance against a variety of pathogens, including viruses, bacteria, fungi and nematodes. Some of these techniques involve using gene products from pathogens themselves, as in the case of virus resistant cassava or insect resistant corn. Others will take advantage of evoking systemic defence pathways already inherent in the plant (Gonsalves, 2002, Lay *et al.*, 2003, Gill *et al.*, 1992). Pathogen detection and disease resistance will also be managed by nanotechnology. For example, nanosensors can be utilized to detect plant pathogens, and nanoparticles can encapsulate pesticides and release them on crops or in insects upon consumption in a controlled fashion ([google.com/site/isinanoicarnaip/](http://google.com/site/isinanoicarnaip/)).

#### **4. Biofortified and other nutritionally enhanced foods**

One way to address the ever growing need for more food crops is to nutritionally enhance those crops which are currently considered to be staples for the world's poor. By producing biofortified rice, wheat and corn, the principal grains which feed much of the human race today, with increased mineral and vitamin content, the nutritional status for those who have little variety available in their diet can be improved. The generation of plants with enhanced micronutrient content can thus be a means to support those whose food supply may dwindle with respect to diversity in the face of climate change. For example, vitamin A deficiency causes approximately 500,000 cases of blindness in children. By increasing the vitamin A content of rice and other staple crops, this number can be greatly reduced (Mayer, 2007). Other examples of biofortification strategies include zinc and iron enriched corn, cassava and rice, or calcium-enriched carrots and tomatoes (Cockell, 2007, Morris, *et al.*, 2008, Naqvi *et al.*, 2009).

Biofortified foods can be produced either through the generation of transgenic plants which possess additional biosynthetic pathways, such as vitamin A-enriched 'Golden Rice' or by altering the general physiology of the plant in such a way that it is able to extract more micro-nutrients from the soil, such as iron-enriched wheat (Figure 3). The design and generation of plants which accumulate more vitamins and minerals can also be beneficial for the health of the plant itself. Plants which are nutrient-rich are better able to weather more

extreme environmental conditions imposed by climate change. Plants which are nutrient rich exhibit vigorous growth, better yield and more resistance to diseases as well (Welch, & Graham, 2004, Bouis, 2003). Biofortified foods can be easily incorporated into the dietary habits and farming programs of the rural poor of developing countries. People who would have access to biofortified foods may very well be better prepared to withstand deleterious effects on their livelihoods due to climate change (Hotz & McClafferty, 2007, King 2002, Gilani & Nasim, 2007, Nestel, et al., 2006, Zhu, et al., 2007, Jeong, & Guerinot, 2008).



<http://www.flickr.com/photos/ricephotos/5516789000/in/set-72157626241604366>

Fig. 3. Golden Rice grain compared to white rice grain in screenhouse of Golden Rice plants.

## 5. Biopharmaceuticals produced in plants

Climate change is predicted to bring more drought, greater salinity, and higher temperatures to countries where people are most vulnerable. A significant proportion of people in these countries are malnourished today, and more problems in this regard can be expected as food prices fluctuate and food security becomes more and more difficult to achieve. People who are undernourished or malnourished are less likely to fend off infectious diseases, and the challenge of providing sufficient vaccines and other medicines is already difficult to meet. Plants can help to rise to this challenge through their ability to act as production platforms for biopharmaceuticals. Indeed, both food and non-food crops are currently being used to produce vaccine proteins against these infectious diseases which are the greatest causes of infant mortality in the Third World today (Hefferon, 2009). Plant made vaccines which target common diarrheal diseases such as Norwalk Virus, enterotoxigenic *E.*

*coli*, cholera, and rotavirus have all been constructed and have shown promising results in preliminary human clinical trials. These vaccines can be produced rapidly, are inexpensive, can be taken by oral consumption and require no syringes or medical personnel to administer them (Tacket, 2007). These attributes make plant-derived vaccines very attractive for distribution to developing countries. Monoclonal antibodies can also be produced using plant-based systems. Diseases such as rabies, a problem in developing countries but not so much in the West, may be better addressed (Modelska et al., 1998). Other diseases such as hookworm are often not given priority for funding by the West; the inexpensiveness of plant-based production platforms offers an alternative approach for research and development. Hepatitis B Virus and human papillomavirus also represent significant problems in developing countries; plant-made vaccines offer one feasible means by which to combat them (Thanavala, 2005, Venuti, 2009).

## 6. Alternative approaches to farming to address climate change

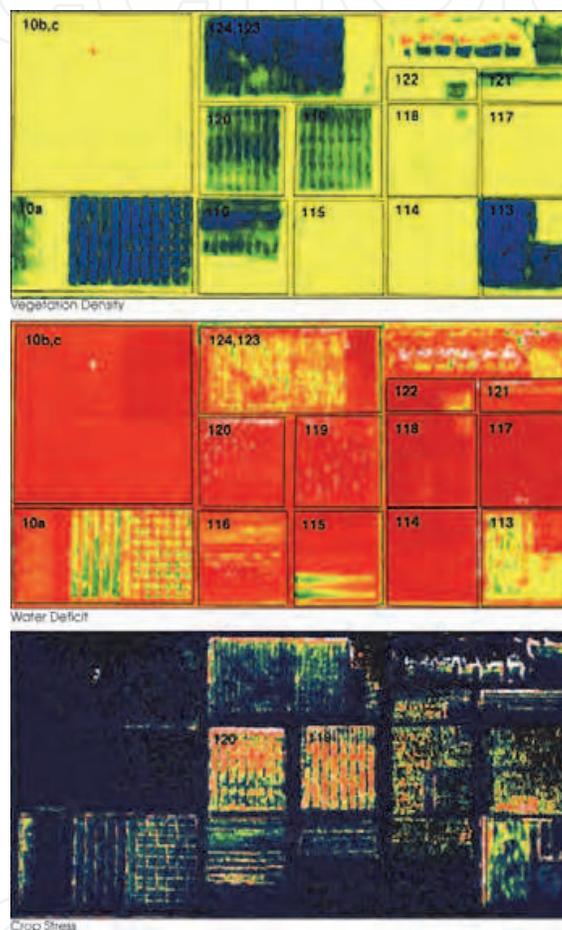
Newer varieties of plants which are more disease resistant, more nutritious, and better able to withstand droughts, high temperature, and high salinity environments are required immediately to prevent humanitarian disaster in the face of climate change. Modern plant breeding strategies have enabled agricultural researchers to develop new strategies to search for and identify traits which could help crop plants withstand extreme environmental conditions. For example, examination of the genetic material from wild relatives of crops has resulted in the recovery of a number of useful genes which have been lost over the course of crop evolution. Retrieval of these old 'wild' genes and their re-incorporation into current crops may facilitate the ability of these crops to adapt and flourish in a rapidly changing environment (Pennisi, 2010). The selection of novel plant traits has been further hastened by the use of automated breeding systems ([www.lemnatec.com](http://www.lemnatec.com)). Through robotics, young plants can be exposed to a specific set of environmental conditions and then be selected for their ability to tolerate stress, maintain high yield, etc., without the requirement of lengthy field tests. Furthermore, new genomics approaches such as marker assisted selection enables desired traits that would help future crops overcome environmental stresses to be identified and followed through breeding strategies (Pennisi, 2010, Baulcombe, 2010).

There are other means by which to increase crop production besides changing the traits of the crops themselves. Precision agriculture, for example, refers to new farming methods based on optimizing resources and minimizing inputs, including water and fertilizer. Precision agriculture can include sophisticated devices such as GPS to identify factors ranging from moisture and nutrient content of soils to pest infestation of a given crop (Figure 4). Using this approach, optimal inputs can be applied to a specific region of a given crop when required, rather than uniformly and at predetermined times across the entire field, whether the crop requires inputs or not. The great advantage of this technique is the avoidance of overuse of pesticides, herbicides, fertilizer and water ([earthobservatory.nasa.gov](http://earthobservatory.nasa.gov), [www.ghcc.msfc.nasa.gov](http://www.ghcc.msfc.nasa.gov)).

The same principles of precision farming can also be applied to developing countries, without the requirement of advanced technologies. For example, the concept of drip irrigation, a practice by which small amounts of water are applied to plant root systems by a network of irrigation pipes, has been demonstrated to work successfully for drought-prone areas (Figure 5). Similarly, some resource-poor countries utilize a farming technique whereby tiny amounts of fertilizer are applied to the roots of crops at specific times in the growing season. These low-tech farming practices have enabled farmers who have poor

access to water or artificial fertilizers to make the most of their crop yield (Mara Hvistendahl, 2010, Nature Editorial 2010).

Better management of the high percentage of food that currently goes to waste could also have a beneficial impact on achieving food security. While excess food waste in the supermarket is clearly a problem in industrialized countries, in the Third World, food crops are often spoiled in the field before they are harvested, infected with insects or mold while stored in primitive facilities, or over-ripen during inefficient transport to the marketplace. All of these bottlenecks need to be addressed to prevent excess food waste and improve food availability (Parfitt et al., 2010).



These three false-color images demonstrate some of the applications of remote sensing in precision farming. The goal of precision farming is to improve farmers' profits and harvest yields while reducing the negative impacts of farming on the environment that come from over-application of chemicals. The images were acquired by the Daedalus sensor aboard a NASA aircraft flying over the Maricopa Agricultural Center in Arizona. The top image (vegetation density) shows the color variations determined by crop density (also referred to as "Normalized Difference Vegetation Index", or NDVI), where dark blues and greens indicate lush vegetation and reds show areas of bare soil.

The middle image (water deficit) is a map of water deficit, derived from the Daedalus' reflectance and temperature measurements. Greens and blues indicate wet soil and reds are dry soil.

The bottom image (crop stress) shows where crops are under serious stress, as is particularly the case in Fields 120 and 119 (indicated by red and yellow pixels). These fields were due to be irrigated the following day. This file is in the public domain because it was created by NASA. NASA copyright policy states that "NASA material is not protected by copyright unless noted".

Fig. 4. Precision Farming.

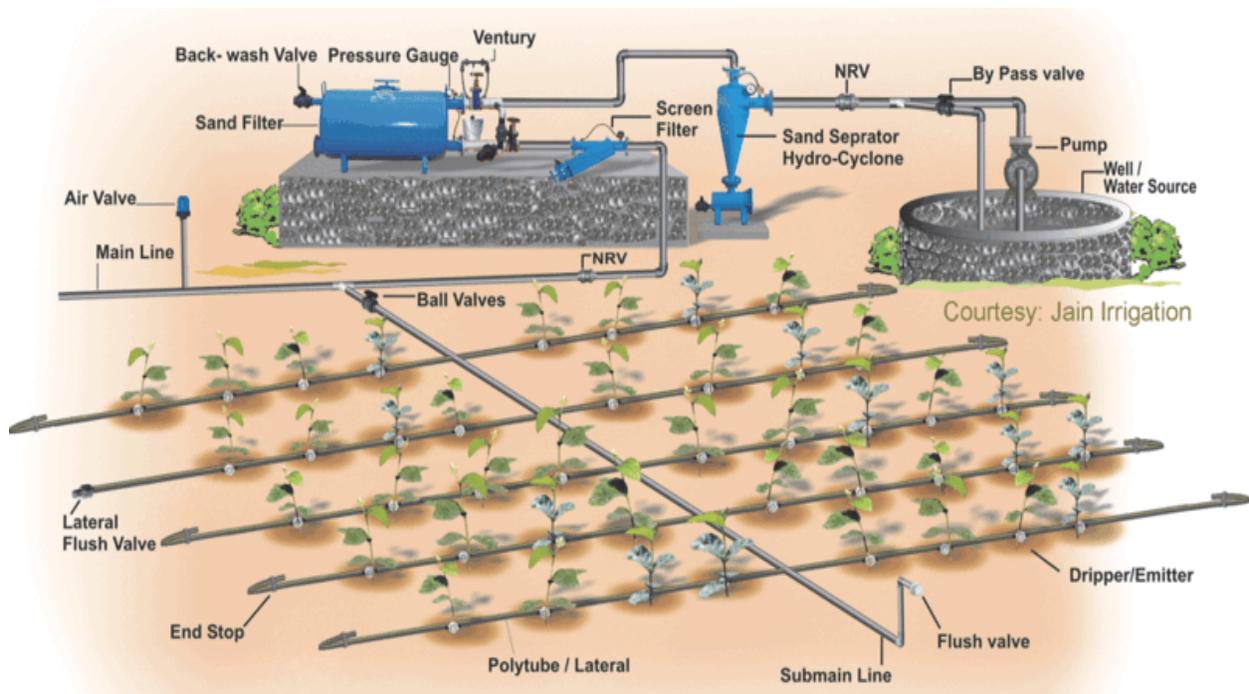


Fig. 5. Drip Irrigation.

## 7. Climate change and non-food crops

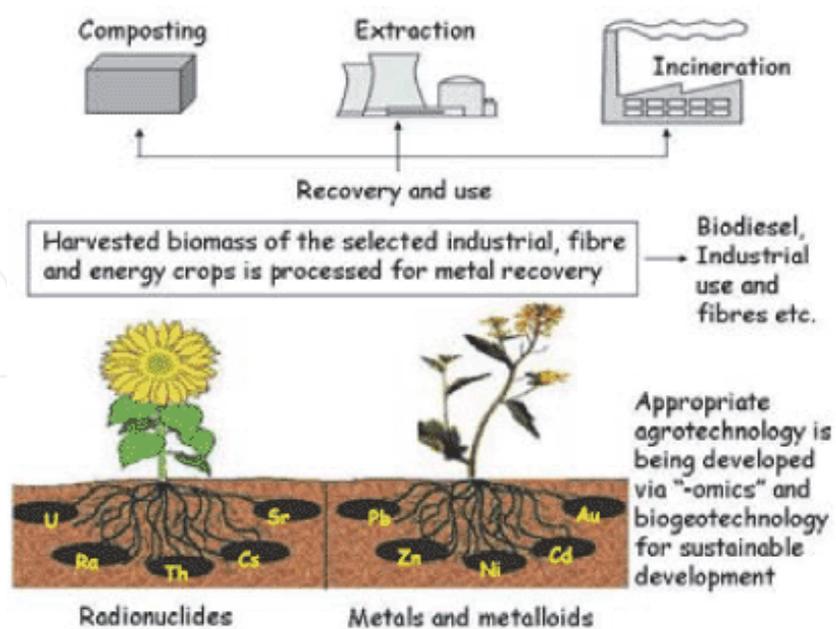
Non-food crops are also being examined as a means to address climate change. The use of biofuel as an alternative energy source is at the height of controversy. While ethanol production from crops such as corn may indeed provide a substitute for fossil fuels, they unfortunately also compete with corn grown as a food crop and in fact drive up food prices, thus adding to the misery of the world's poor. One option is to use other non-food plants for biofuel production. Switchgrass, for example, can be grown on suboptimal land that cannot be used by corn or other food crops, and produces fuel less expensively than either petroleum or corn (Figure 6) (Bouton, 2007). Algae is another plant source for biofuel which would not negatively impact the world's food supply. These examples represent up-and-coming technologies which will soon move up to the forefront of alternative energy development (Beer *et al.*, 2009).

Other non-food crops address the reduction in arable land acreage available as a result of climate change; these plants are under development for phytoremediation purposes. Man-made pollutants such as heavy metals which have been added to soil and water have reduced the availability of much needed fertile land. Some plant species have the capacity to uptake heavy metals through their root systems and accumulate them in foliage or other tissues. These plants can then be harvested to rid the land of contaminants, thus providing an increase in valuable, arable farmland (Figure 7) (Wu *et al.*, 2007, Memon & Schröder, 2009).



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Fig. 6. Switchgrass.



<http://www.scielo.br/img/revistas/bjpp/v17n1/a05fig01.gif>

Fig. 7. Phytoremediation: green technology for the clean up of toxic metals in the environment.

## 8. Conclusions

Climate change brings with it some daunting challenges. More food must be produced on less arable land than is available today. New agricultural technologies and farming practices must be developed and implemented. This chapter has attempted to address some of the strategies currently under development in the agricultural sciences. One way to achieve global food security requires the utilization of novel plant breeding strategies which will quickly find helpful traits that enable plants to thrive under adverse environmental conditions. Biotechnology will play a paramount role in these approaches. Revolutionary farming techniques, led by precision agriculture, will keep crop yields high while maintaining water, pesticide and nitrogen inputs to a minimum. Key food crops have already been biofortified with micronutrients such as iron and vitamin A. Plants are also being actively pursued as production platforms for biopharmaceuticals, and may very well turn out to be a viable solution for providing medicines to those in remote communities. Innovative uses for non-crop plants in biofuel and phytoremediation will also offer alternatives. With these and other strategies in place, the world will be better prepared to address the future challenges that will result from climate change.

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## **Climate Change - Research and Technology for Adaptation and Mitigation**

Edited by Dr Juan Blanco

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This book provides an interdisciplinary view of how to prepare the ecological and socio-economic systems to the reality of climate change. Scientifically sound tools are needed to predict its effects on regional, rather than global, scales, as it is the level at which socio-economic plans are designed and natural ecosystem reacts. The first section of this book describes a series of methods and models to downscale the global predictions of climate change, estimate its effects on biophysical systems and monitor the changes as they occur. To reduce the magnitude of these changes, new ways of economic activity must be implemented. The second section of this book explores different options to reduce greenhouse emissions from activities such as forestry, industry and urban development. However, it is becoming increasingly clear that climate change can be minimized, but not avoided, and therefore the socio-economic systems around the world will have to adapt to the new conditions to reduce the adverse impacts to the minimum. The last section of this book explores some options for adaptation.

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