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Review

Biotechnology and industrial ecology: new challenges for a changing global environment

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Human causes of global environmental change are invariably linked to inconsistencies in the relationship between industrial activities and ecological systems (industrial ecology). The choice of fuel materials used in the energy industry is directly responsible for increases in the atmospheric concentration of carbon dioxide, resulting in the current trend of global warming. The dependency of the agricultural industry on chemicals to sustain productivity in marginal landscapes has led to a global-scale contamination of the environment with toxic pesticides and with nutrient fertilizers that are changing the course of biogeochemical cycles. One of the strategies proposed to mitigate climate change is to lower dependency on fossil fuels by substituting renewable biomass. This strategy has several co- benefits for human health and the environment because it supports investments in agricultural biotechnology while reducing the adverse health impacts of combustion byproducts of fossil fuels. The strategy has limited likelihood for success if “run-away” climate change modifies the ecosystem sufficiently to impact agricultural productivity. The development and global implementation of biotechnological approaches can contribute urgently needed solutions to problems associated with inefficiencies in the industrial ecology of agricultural and energy resources. The necessary biotechnological protocols are available, but scale-up techniques are limiting, particularly with respect to the cultivation and processing of alternative non-recalcitrant raw materials in stressful environments.

Key words: Biotechnology, industrial ecology, energy, agriculture, biofuels, climate change, desertification, genetic engineering.

INTRODUCTION

The human population is growing at an exponential rate and average per capita consumption of natural resources is also increasing. These growth patterns are leading to rapid changes in global environmental conditions accompanied by societal impacts that are unevenly distributed across regions and countries (Ogunseitan, 2003, 2004). In Africa, the impacts of climate change are becoming increasing apparent, placing an additional strain on an already stressed interaction between human societies and the ecosystem. For example, satellite monitoring of Lake Chad since 1963 demonstrate a rapid shrinkage of this water resource that has traditionally served the populations of four large countries, namely Cameroon, Chad, Niger, and Nigeria (Figure 1). The shrinking of Lake Chad results from excessive irrigation to support an unsustainable agricultural industry, and from reduced precipitation that has been attributed to climate change (Coe and Foley, 2001). The African continent is also susceptible to global impacts of climate change through the release of dust storms from the Sahara desert (Figure 2). These dust storms have also been associated with diseases affecting coral reefs in

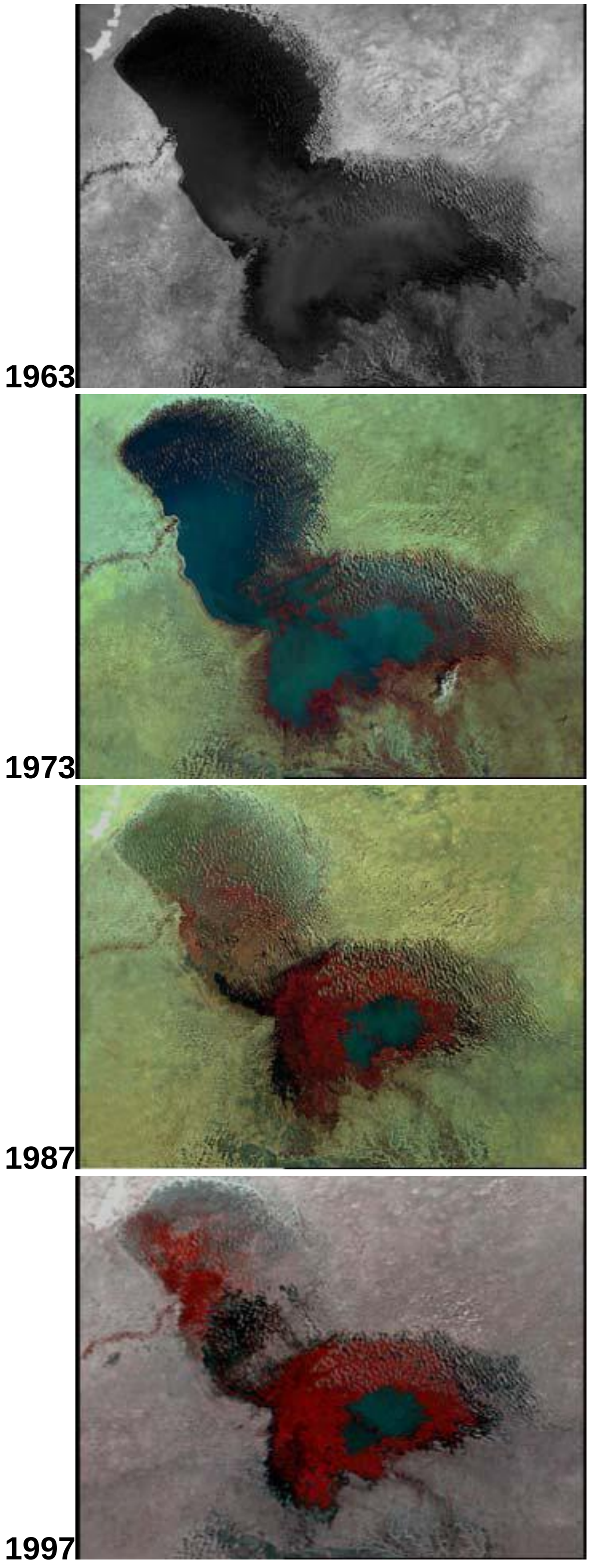

Figure 1. Time series images showing the shrinkage of Lake Chad which serves the agricultural industry in four West African countries. The current lake area is ~ 1,250 km^2, down from ~ 25,000 km^2 in 1963. Images are by courtesy of NASA.

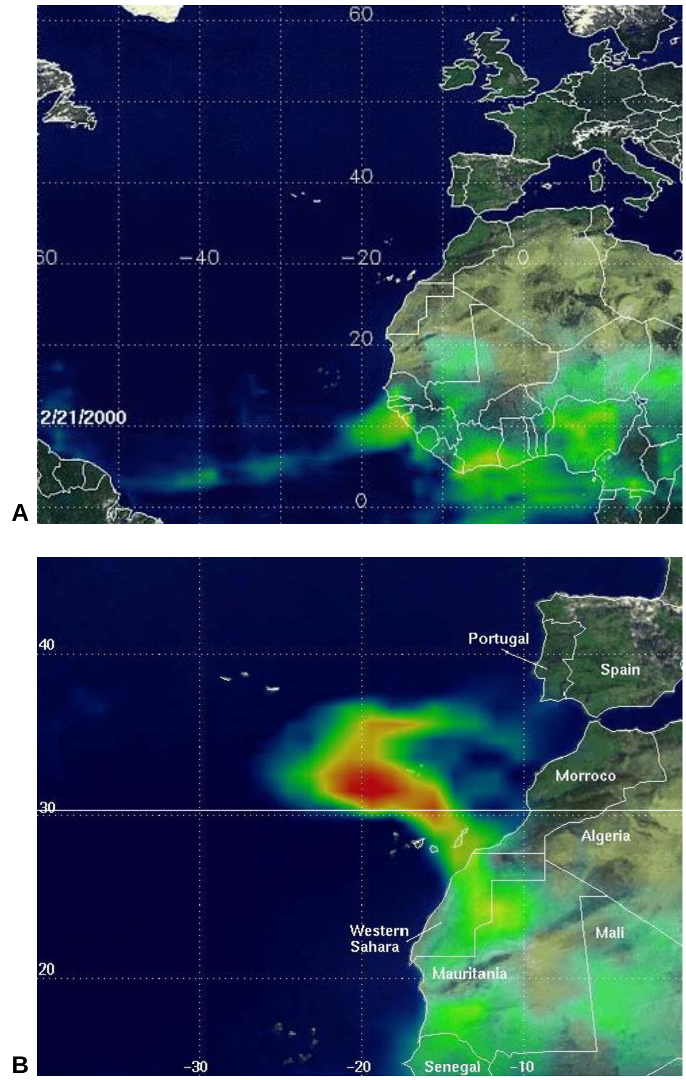

Figure 2. Aerosolized dust from the Sahara Desert as captured by NASA's Total Ozone Mapping Spectrometer (TOMS) affects all countries south of the desert, reaching South America (Panel A), and crosses the Pacific Ocean, reaching the Carribean islands (Panel B). Global climate change events may exacerbate desertification, thereby increasing the impact of aerosol on human and ecosystem health. Images are by courtesy of NASA (Dr. Richard McPeters, Principal Investigator for Earth Probe TOMS).

the carribean, and with plant diseases in the Americas (Garrison et al., 2003).

Sustainable solutions to social and environmental problems associated with climate change, including desertification, loss of biodiversity, ecotoxicity, and shrinking water resources requires concerted efforts at many different fronts, many of which will involve substantial investments in biotechnology. The relationship between biotechnology and industrial ecology is multifaceted, but the intricacies of this relationship have not been explored extensively. A diagrammatic framework of the role of biotechnology as

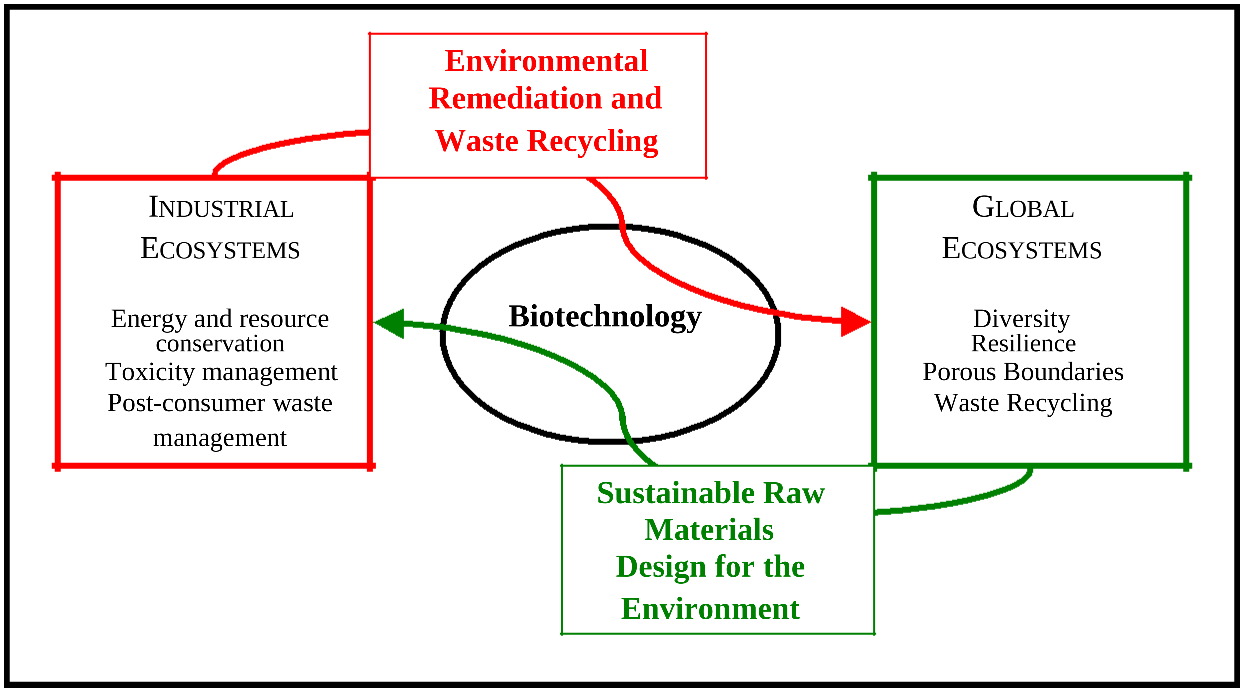

Figure 3. Biotechnology links industrial and ecological systems through the provision of tools for cultivating sustainable raw materials for industrial processes, and the recycling of waste products. The ideal industrial development strategy is based on an ecosystem model where diversity is optimized in relation to available functions.

the middle ground between ecological systems and industrial processes is presented in Figure 3. Stable ecosystems are characterized by high levels of species and functional diversity; by complete recycling of waste products; and by niche optimization. In contrast, most industrial institutions are highly specialized with limited opportunities for interactions among different industries. In addition, many industries, including the agriculture and energy industries, use and/or produce copious amounts of toxic recalcitrant chemicals, and are poorly fitted with the natural environments that provide raw materials and receive waste products (Ogunseitan, 2002; Ogunseitan and Odeyemi, 1985; Solomon et al., 2000). Emerging strategies to improve upon the present status of global industrial ecology aim to achieve principles of operation that are modeled after natural ecosystems (Thomas et al., 2003). Progress toward this goal, especially in developing countries, will require a new way of thinking about how best to integrate emerging biotechnologies such as genomics, proteomics and genetic engineering into industrial processes that mitigate against the impacts of global environmental change. This paper provides an overview of the current challenges by addressing some cases studies in the agriculture and energy industries in light of the linkages between biotechnology and industrial ecology.

AGRICULTURAL BIOTECHNOLOGY AND INDUSTRIAL ECOLOGY

Sustainable food production is of paramount importance in promoting public health and the economic base of many African countries. Climatic change is affecting food production through modifications to the growing season, expansion of desert landscapes, lengthening of drought periods, and in some instances widening of river flood basins and the geographical range of insect pests (IPCC 2001a). Biotechnological manipulation of plants can aid in the production of stress-resistance crops, and the cultivation of drought resistant plant crops will be needed to support the continuation of local agriculture in the Lake Chad basin in order to reduce the potentials for massive displacement of human capital and international conflict. Several lines of biotechnology research being conducted at the International Institutes for Tropical Agriculture (IITA) and other programs of the Consultative Group on International Agricultural Research (CGIAR) are relevant to the mitigation of climate change impacts. For example, under the “Desert Margins Program”, the field testing of transgenic cowpea plants was initiated in 2003. In addition, two extra- early maize varieties with combined resistance to drought and *Striga* and18% higher grain yield than the widely grown variety (TZEE-

WSR BC5) were released in some countries (CGIAR, 2003).

The biotechnological manipulation of plant resistance to stressful environments, including drought conditions, typically involves the over-expression of stress response genes. For example, the late embryogenesis protein gene (HVA1) from barley (*Hordeum vulgare* L.) is associated with significant increases in the level of tolerance to water deficit and salinity. Genetically engineered plants that over-express HVA1 maintains higher growth rates than non -transformed control plants under stress conditions (Xu et al., 1996). HVA1 is induced by stress conditions, and by abscisic acid, a plant hormone that regulates transpiration and embryogenesis (Figure 4). Abscisic acid contains long stretches of amphipathic alpha-helical structure which presumably aids its function in conserving water by reducing water loss; in reducing the rate of plant growth; and in mediating adaptive responses (Liu et al., 2003). Along with gibberellins, abscisic acid also governs the transition from embryogenesis to seed germination, where they both play a role in the high resistance of plant embryos to environmental stresses such as drought.

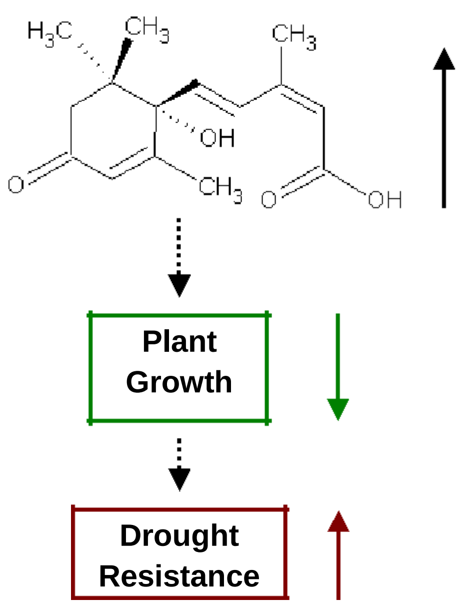

Figure 4. Chemical structure of the plant hormone abscisic acid unit, which protects against drought. Arrows pointing up indicate increase in concentration or expression. Down pointing arrow indicates suppression.

Although the function of HVA1 has been engineered into many crop plants to enhance drought resistance, large scale field testing of the genetically-engineered varieties is limited. Public acceptance of genetically engineered food products has been extremely controversial with major divisions in public opinion between the European Union and the United States. The governments of many developing countries are yet to decide on the possibility of cultivating genetically engineered crops for public consumption (Dr. Ken Dashiell, IITA, Ibadan, personal communication). The resistance to environmental release of genetically engineered non-food crop plants is perhaps less controversial, but application of the precautionary principle requires that the results of exhaustive scientific field tests must be taken into consideration to avoid long-term ecological impacts. The unresolved question is whether concern for emergency conditions that are certain to follow the complete dryness of life-support water systems such as Lake Chad should override the precaution of cultivating genetically engineered drought resistant plants as a strategy to mitigate societal impacts.

ENERGY BIOTECHNOLOGY AND INDUSTRIAL ECOLOGY

The prosperity of several national economies depends on un-interrupted supplies of fossil fuels such as petroleum, coal, and natural gas. These raw materials cannot be easily replenished, and their combustion is accompanied by environmental contamination with respirable particulate matter, excess carbon dioxide, and in certain cases, toxic metals such as lead and manganese additives to petroleum, and mercury from coal-based power plants (Bhuie et al., 2004; Ogunseitan et al., 2003). The global impacts of these pollution problems has instigated international action to deal with greenhouse gas-induced climate change, in part through the encouragement of fuel sources that exhibit short-term recyclability (IPCC, 2001b). Such fuels require the large scale cultivation of plants that serve as the source of cellulosic materials, which can be further processed to produce ethanol fuels. It is controversial whether countries that have to deal with shrinking land resources for growing food should switch their economy to the cultivation of raw materials for biological fuels such as ethanol (Thomas and Kwong, 2001). Nevertheless, this option warrants closer evaluation from the perspective of biotechnological strategies that can potentially optimize the balance between fuel and food production from limited land resources.

Many microorganisms produce extracellular enzymes capable of degrading cellulose. Microbial degradation of cellulose occurs outside the cell because cellulose molecules are not very soluble, and they have molecular weights as high as 1.8 million, consisting of up to 10,000 β-1,4 linked glucose monomers. Cellulose-degrading extracellular enzymes are diverse and varied in their mode of action. For example, β -1,4-endoglucanase attacks cellulose polymers randomly; β-1,4-exoglucanase requires access to the reducing end of the molecule to release disaccharide cellobiose; and β-glucosidase, hydrolyzes cellobiose to glucose. These enzymes are ubiquitous in microbial communities, but there is considerable polymorphism in their forms, functions, and degradative kinetics. The cellulase system of *Trichoderma reesei*, is one of the most widely investigated in terms of biotechnological applications. Extensive research programs have explored strategies for reducing the cost and effectiveness of cellulase enzymes in bioethanol production. The current cost estimate for cellulase ranges from 0.1 to 0.3 US$ per liter of ethanol produced, but biotechnological approaches can presumably reduce cellulase cost to less than 0.01 US$ per liter of ethanol. Such an improvement will require a tenfold increase in specific activity, production efficiency, or both (Sheehan and Himmel, 1999). Ethanol at this price costs a lot less than many developing countries are paying for petroleum – even in countries where the petroleum industry is heavily subsidized by government revenue. In addition, the production of ethanol -based fuel is less likely than petroleum mining to lead to large-scale environmental degradation (Odeyemi and Ogunseitan, 1985). In terms of ethanol production efficiency, a 90:9:1 mixture of a cellobiohydrolase from *T. reesei* (CBH I), a heat-tolerant endoglucanase from *Acidothermus cellulolyticus* (EI), and a β -D- glucosidase was capable of complete saccharification of cellulose in acidified yellow poplar after 5 days. This discovery represented an important breakthrough because it demonstrated for the first time that polymorphic cellulase systems can be engineered for specific pretreated biomass materials (Baker et al., 1998).

New discoveries continue to be made about strategies to produce biological fuels cheaply and efficiently. For example, Chaudhuri and Lovley (2003) demonstrated that the energy stored in crops such as corn can be tapped more directly through a conversion to electrical energy while bypassing products such as ethanol and hydrogen. The investigators relied on existing biofuel cells in which whole microbial cells or isolated redox enzymes catalyze carbohydrate oxidation, and on a novel microorganism, *Rhodoferax ferrireducens*, which can oxidize glucose to carbon dioxide while quantitatively transferring electrons to graphite electrodes without the need for an electron-shuttling mediator. Bacterial growth is supported by energy derived from the electron transfer process, leading to a sustainable power production from such configurations. The scale-up of this process has not been tried, but its preliminary success should serve as sufficient inducement for agencies engaged with global technology transfer in the energy sector. New ways are also being developed to use existing natural resources to generate more traditional fuels. For example, Sang and co-workers (2003) demonstrated that palm oil, a renewable source that is common in tropical regions, can be processed at normal atmospheric pressure and temperature of 450^{o}C to produce biofuel in a fixed-bed microreactor. The palm oil-based product contained hydrocarbons corresponding to gasoline, kerosene, and diesel boiling point range. The maximum conversion of palm oil was found to be 99 wt% with a gasoline yield of 48 wt%. This is a modest yield, given that palm oil is a widely used food resource, and this particular application may not be economically sustainable.

CONCLUSION

Large scale production of ethanol and other sustainable biofuels for use as industrial and domestic sectors has been implemented successfully in many parts of the world, especially in Brazil and the United States. In those cases, the incentives were to supplement a robust economy with a cheap and readily available source of energy, and there were no drastic negative impacts on food production due to the diversion of land and agricultural infrastructure. In several developing countries, however, considerable planning effort needs to be focused on maximizing the benefits of land use decisions because of the intricate linkages between local economy, and public health and welfare. The current practice, in many parts of Africa, of obtaining fuel from forest wood is clearly unsustainable because it contributes to rapidly advancing deforestation (Bewket, 2003). Similarly, the dependence on dry manure as a direct source of fuel suffers when drought periods are extended. These problematic conditions will only be exacerbated by changes to the global climate. Given the mounting evidence of the entanglement between the agriculture and energy industries, it is important to configure the relationship in a way that mitigates environmental change while securing food and fuel resources. Biotechnology has a central role to play in this new configuration. In the specific cases discussed here, investments in genetic engineering to broaden the scope of drought resistant plants, and to produce energy fuels from such plants are paramount.

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