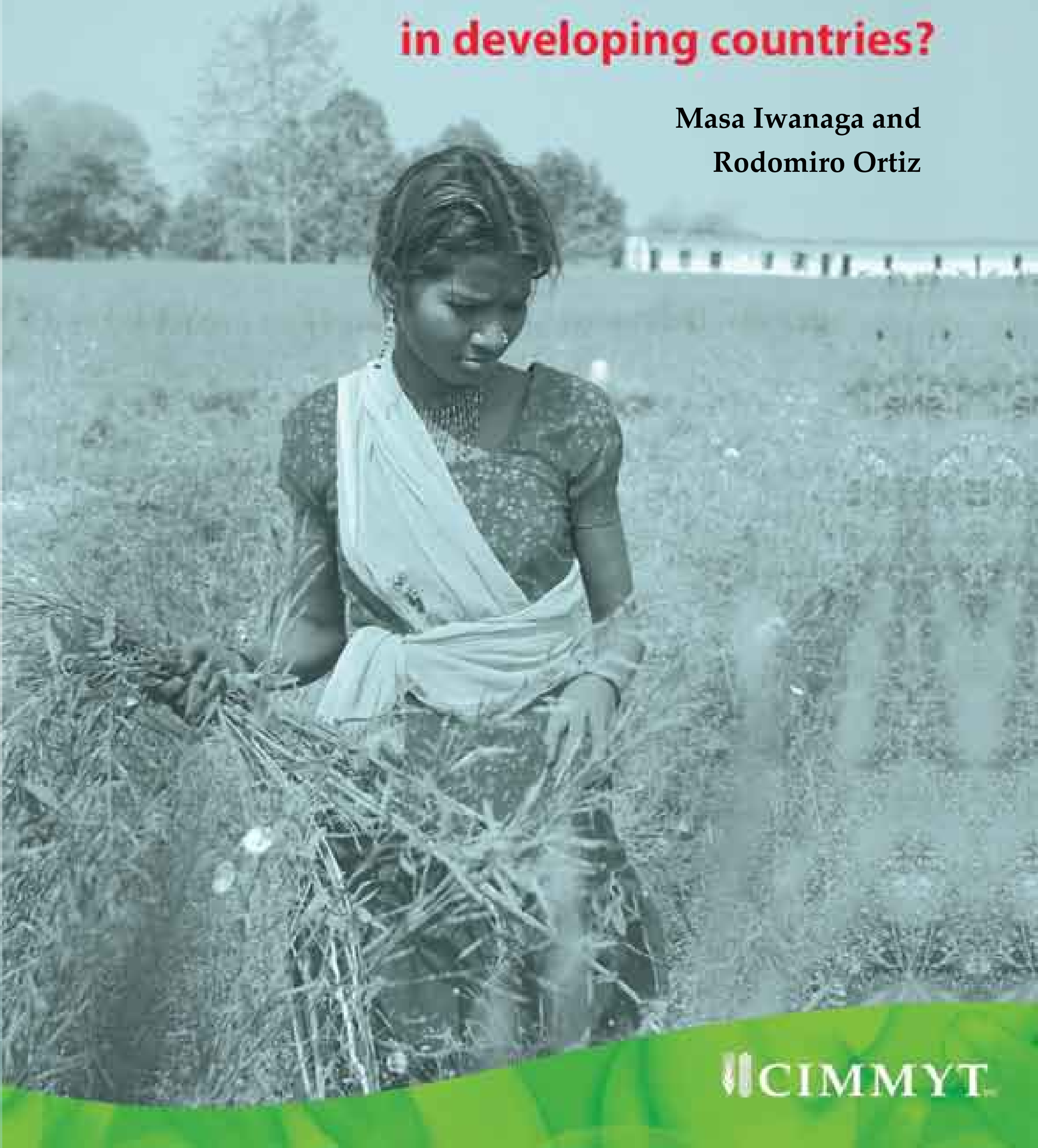
International Maize and Wheat Improvement Center

Should energy be a product of 21st century agriculture in developing countries?

Masa Iwanaga and
Rodomiro Ortiz



CIMMYT

Should energy be a product of 21st century agriculture in developing countries?[1]

Masa Iwanaga and Rodomiro Ortiz [2]

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[1] Keynote on Session "Food Security vs. Biofuels in Asia" in the Expert Consultation on Biofuels, Co-sponsored by APAARI, CIMMYT, IRRI and ICRISAT, International Rice Research Institute, Los Baños, Philippines, 27-29 August 2007

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SUMMARY

Recent policies fostering use of alternative, renewable energy sources in the industrialized world confront developing countries with diverse opportunities and challenges: how to integrate with potential biofuel markets, deal with impacts on food security, alleviate poverty, and manage crop and natural resources sustainably. Biofuels should form part of a global, cross-cutting agenda of agricultural research, involving partners in the farming and energy sectors. Work should generate public goods, including broad-based knowledge, enabling technology, and tools for assessment. The agricultural systems required will feature, among other things, sustainable production and efficient use of biomass, partitioning it among energy, feed, food and CO_2 fixation demands. They should be more efficient and pro-poor, and use existing farmland or marginal (dry, waterlogged, saline) tracts. Organizations such as the Consultative Group on International Agricultural Research (CGIAR) and its research centers may play the following roles:

- **Developer** of analytical tools.
- Policy **analyst** and **advocate** for bio-energy, livelihoods and food security.
- **Provider** of allele sources or advanced lines and populations of improved crop cultivars.
- **Catalyzer** of research on useful crop traits and effective crop-resource management.
- Proprietary technology **broker** to ensure bio-energy at the village level.
- Knowledge-sharing **facilitator** throughout the bio-energy value chain.
- Knowledge **integrator** for complex food-feed-fiber-fuel environmental service systems.

Public-private partnerships will have to engage the broader agricultural and development policy research community, addressing the following issues in ways that benefit farmers and consumers:

- Possible tradeoffs of food / feed / fiber versus fuel. Under what conditions could the demand for biofuels—especially from food crop sources—increase food or feed prices and affect food security, locally or globally?
- Environmental costing of biofuels. The energy output should be higher than the energy used to produce a given biofuel.
- Less water-demanding biofuels than current alternatives.
- Environmental services: eco-friendly biofuels may reduce C-emissions, mitigating climate change.
- Opportunity windows and risks from biofuels, particularly for resource-poor producers and consumers.
- Energy institutions and bio-energy management.
- Policy-driven versus user-demand effects. What are the roles of governments and their expectations in the face of unstable and rising oil prices? Other political or economic considerations?
- Partnerships and roles for international, regional, or national research organizations: how to foster innovative research for development to produce food and energy, while expanding the ecologically-friendly use of marginal or waste lands, increasing incomes and providing new labor options for the poor.
- The role of public agricultural research organizations to speed the development and adoption of second generation, ligno-cellulose biofuel technologies.

The agenda for crop improvement will include increasing plant grain and biomass productivity, optimizing the chemical and physical attributes of biofuel sources, and improving specific traits in first- and second-generation biofuel crops, within a framework of sustainable agriculture. Frontier approaches should be applied to study the possible advantages of perennial biofuel crops that are more photosynthetically productive, entail lower input costs, and improve soil nutrient input and retention. Through alliances with the bio-energy industry, research should also adapt industrial processes to biomass sources and sources to promising processes.

> *"The fuel of the future is going to come from apples, weeds, sawdust – almost anything. There is fuel in every bit of vegetable matter that can be fermented."*
>
> **Henry Ford, 1925**

Converting agricultural production to energy has become an important and well-funded global research goal,[3] as petroleum oil reserves fall and prices rise. Indeed, rising fuel prices, growing energy demand, and concerns over global warming from greenhouse gas emissions and domestic energy security have put bio-energy at large and crop biofuels in particular in the research agenda for agriculture worldwide.[4]

Biofuels are attracting great attention in Asia, for example, where steady population growth and attendant energy demands outstrip supplies from fossil fuels. Per capita energy use by the two giants, China and India, pose local and global ecological hazards.[5] Developing world governments elsewhere are showing a keen interest in renewable energy sources, particularly biofuels, both to reduce expensive fossil-fuel imports and to expand markets for their crops. Hence, global demands for clean energy appear to coincide with long-held interests in expanding agricultural markets to benefit the rural poor. Achieving this without endangering the environment or affordable food and feed supplies will require the creation of complex, cross-sector linkages and partnerships, creating and strengthening strategic alliances among public and private organizations and the agriculture and energy sectors.[6]

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[3] E. Kintisch (2007) *Science* 315:747

[4] S.E. Koonin (2006) *Science* 311:435

[5] IPCC (2007) *Climate Change 2007: Climate Change Impacts, Adaptation and Vulnerability*, Intergovernmental Panel on Climate Change 4th Assessment Report – Working Group II

[6] S. Herrera (2006) *Nature Biotechnology* 24:715–720

THE IMPACT OF GOVERNMENT POLICY

Government policy, sometimes in compliance with international agreements such as the Kyoto Protocol, appears to be driving biofuel use. The government of Brazil launched its National Fuel Alcohol Program in the mid-1970s, and by 1980 ethanol use overtook that of gasoline. Since price liberalization in 1999, ethanol has cost a third less than gasoline, and Brazil is now the world's second-leading ethanol producer and exporter, using sugarcane as feedstock (Table 1). More recently, the US biofuel industry, the world leader, expanded as a result of a Presidential Initiative on Bio-energy. In mid-2006 there were 81 plants ranging in capacity from 3.8 to 1,140 million liters of annual output and half of which are farmer-owned. In 2005, 36 million tons of maize—fully 13% of the US maize crop—were used to produce 16.3 billion liters of ethanol. Since 2001, China, the third-largest ethanol producer worldwide, has promoted ethanol-based fuel on a pilot basis in five cities in its central and northeastern regions. The Jilin Tianhe Ethanol Distillery, the largest in the world, is producing 912 million liters per year, and has a potential final capacity of 1,216 million liters per year. China has used maize (2.1% of its output), and wheat (0.7% of its output) as feedstocks, but is switching to crops such as cassava, potato, sweetpotato, and sweet sorghum. Similarly, the government of India mandated the use of biofuels in nine states and enacted an excise duty exemption for ethanol. Sugarcane is still the main feedstock and

Table 1. Selected leading ethanol producers in the world (2005)

Country	Million of liters	World output share (%)
USA	16,203.2	35.1
Brazil	16,062.6	34.8
China	3,815.2	8.3
India	1,706.2	3.7
Thailand	300.2	0.6
Indonesia	171	0.4
Australia	125.4	0.3
Japan	114	0.2
Pakistan	91.2	0.2
Philippines	83.6	0.2
Total world	**46,170**	

the Indian biofuel industry plans to build 20 new ethanol plants in addition to the 10 existing plants.

Thailand, which uses cassava as main feedstock, approved a 10% ethanol mix starting in 2007, which would boost production to 1,505 million liters. As a result of this national policy, 18 new ethanol plants are being developed, and producers will benefit from tax breaks. The Thai government calculates that a fuel blend would be cheaper per liter than conventional gasoline. Since 2000, Australia has provided tax exemptions and subsidies to ethanol producers, aiming to hit 350 million liters of biofuel by 2010—enough to replace 1% of its total fuel supply.

As in the USA, national policies mean that the price of ethanol will depend mainly on the price of gasoline and on the size of ethanol tax credit, rather than on feedstock prices. Increasing ethanol demand significantly may not affect its price, but would raise feedstock and food prices.

SHAPING A MULTI-SECTOR BIO-ENERGY AGENDA

Because of the value-added incentive it offers farmers, use of food crops as raw material for bio-energy production may significantly change rural livelihoods and grain trade dynamics,[7] but could also adversely affect food and feed supply chains, soil management systems, and environmental conservation.[8] On the other hand, marginal lands currently unsuitable for food production could become important for growing underutilized plant species that are efficient biomass producers in low input systems, thus providing cheaper sources for bio-energy production that do not interfere with current food production systems.[9]

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[7] C. Schubert (2006) *Nature Biotechnology* 24: 777–784

[8] J. Hill *et al.* (2006) *Proceedings National Academy of Sciences, USA* 103:1120611210

[9] A.J. Ragauskas *et al.* (2006) *Science* 311:484–489

Dealing with the complexity of interacting factors across regions, end-user groups, and disciplines demands a holistic approach.[10] Only in this way will it be possible for plant breeders to provide appropriate new traits, cultivars, and crops that enhance incomes for developing country farmers, improve efficiency in biofuel processing plants, and minimize negative impacts on grain production and prices, livestock farming, soil conservation, and the environment. Governments will thus be able to enact policies for cheap, environmentally-friendly biofuels that provide enhanced income to farmers and processors and a long-term cheaper alternative to petroleum oil-based fuels.[11]

Plant breeders will need to consider vegetative biomass traits rather than solely on grain, to keep food prices from rising.[12] Agronomists will need to develop soil management systems that require less residual biomass yet are in line conservation agriculture principles.[13] Livestock scientists will need to optimize feed and fodder uses in systems where there is a premium on biomass for biofuel production; this at a time when rising incomes are expected to double the demand for meat in developing countries.[14] Socio-economists will need to work with agricultural scientists to suggest the most appropriate agricultural species for use in various rural scenarios, considering trade dynamics, the competition among food, feed, and biofuel markets, and the high prices of petroleum-based fertilizers.[15] Policy advisers and governments need to balance the need for exporting surplus grain versus using it locally for biofuels.[16] Some farmers will benefit from increased incomes through access to new biofuel markets, but resulting higher on food prices[17] will also impact on poor rural and

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[10] J.P. Holdren (2007) *Science* 315:737

[11] United Nations (2007) *Sustainable Bio-energy: A Framework for Decision Makers*. UN-Energy, New York

[12] K. Cassman *et al.* (2006) CAST Commentary QTA2006-3

[13] R.L. Graham *et al.* (2007) *Agronomy Journal* 99:1–11

[14] R. Naylor *et al.* (2005) *Science* 310 :1621–1622

[15] A.A. Vertes *et al.* (2006) *Nature Biotechnology* 24:761–764

[16] A. Elobeid *et al.* (2007) *AgBioForum* 10:11–18

[17] M. Rosegrant *et al.* (2006) *Vision 2020 for Food Agriculture and the Environment – Bio-energy and Agriculture: Promises and Challenges* 14:3

urban consumers.[18] Last but not least, engineers and ecologists will need to calculate the energy costs of using different crops for biofuel production and their differential effects on internationally monitored environmental emissions.[19]

The remainder of this article provides an overview of agricultural research issues, particularly in plant breeding and bioscience, important for the development of an “appropriate” biofuel industry. It also addresses priorities for agricultural research-for-development on biofuels, to maintain a balance between food security, energy production, and agricultural and environmental conservation. Finally, it suggests how such research can best be organized and financed, including the most appropriate role for the Consultative Group on International Agricultural Research (CGIAR) and national research and development institutions.

CROP BREEDING AND BIOFUELS

Today most world ethanol derives from either sucrose or starch. This starch or grain-based bio-ethanol is termed “first-generation” biofuel. There are, to the authors’ knowledge, only a few breeding programs dedicated solely to improve crops as a bio-energy feedstocks.[20] Many programs do target enhanced silage quality, a trait highly associated with improved bio-energy output.

Plant biomass is abundant, renewable, carbon-neutral, and a sustainable source of hydrocarbons. Biomass can therefore fill the gap between energy demand and petroleum availability in the near term, and be a renewable source of hydrogen in the long term. Furthermore, crops can generate more cellulose per hectare than sucrose or starch, suggesting that cellulose feedstocks possess great potential as a fuel source, if “biomass recalcitrance” —i.e., the natural resistance of plant

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[18] C.F. Runge & B. Senauer (2007) *Foreign Affairs* http://www.foreignaffairs.org/20070501faessay86305-p40/c-ford-runge-benjamin-senauer/how-biofuels-could-starve-the-poor.html

[19] A.E. Farrel *et al.* (2006) *Science* 311:506-508

[20] C. Schubert (2006) *Nature Biotechnology* 24 :777–784

cell walls to microbial and enzymatic deconstruction— is overcome, lowering the costs of lignocellulose conversion.[21]

Plant breeders should therefore aim for a crop with a biomass on the order of 15 tons per hectare and traits that maximize fuel yield per land area. Target traits would include those that foster the cheap decomposition of vegetative material and match genes for this purpose in fungi used in cellulose-processing.

The main energy-output traits in the crop genetic enhancement agenda are high levels of cellulose or hemi-cellulose content through increased carbohydrate content, and high biomass through an increased initial capture of light energy or by manipulating nitrogen metabolism genes. Low-input tolerance traits, such as increased water- or nutrient-use efficiency or adaptation to zero or reduced tillage, are needed to ensure a positive energy output, when increasing biomass.

Adapting crops to marginal lands affected by drought, salt, or temperature stresses remains an important target of crop breeding, especially to avoid diverting most of today’s land grown with food staples into biofuel crops, or to account for any switch to biofuel farming of such land in food exporting regions of the world. Likewise, any of the improved traits should also assist in reducing carbon dioxide emissions, release less air pollutants, and should fit into conservation agriculture practices.

WHAT BIOTECHNOLOGY OFFERS

Biotechnology research that addresses farming and industrial needs could contribute significantly to sustainable biofuel production.[22] In this regard, a feedstock plant with reduced lignin levels is one of the main aims for crop genetic enhancement of second-generation biofuel sources.[23] For example, maize’s and sorghum’s *bm* mutants may be

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[21] M.E. Himmel *et al.* (2007) *Science* 315: 804–807

[22] M.W. Weevan & M.C.R. Frassen (2006) *Nature Biotechnology* 24:765–767

[23] M. Sticklen (2006) *Current Opinion in Biotechnology* 17:315–319

used to alter lignin composition and amounts in cell walls.[24] "Omics" sciences (genomics, proteomics, metabolomics) can facilitate the understanding of the lignin biosynthesis pathway, and help molecular breeders to manipulate genes for optimal processing traits. Research to date has shown that many genes are involved in the inheritance of important forage characteristics, such as fiber type and content. Furthermore, there is a tight negative association between lignin content and feedstock value. Other genes of interest include those repressing lignin biosynthesis, reducing lignin content while increasing cellulose, or down-regulating lignin biosynthetic genes that result in cell walls easier to digest by bacteria, thereby doubling sugar release.

Efforts have been made in recent years to produce fermentable sugars utilizing maize stover and fiber as feedstock. An important limitation to the use of maize stover is that it requires pretreatment and hydrolysis to convert its lingo-cellulosic biomass to fermentable monosaccharides. The pretreatment alters macro- and microscopic biomass size and structure, along with chemical composition, so that enzymatic hydrolysis of the cellulose fraction proceeds more rapidly and with greater yield.

DNA markers are short sequences located near genome segments associated with traits of interest. Because they co-segregate with the trait gene, they can be used as a tool in selection. They can assist in discovering genes for traits of interest among the hundreds of thousands of germplasm bank accessions. Finally, such markers are also used to analyze genetic variation, essentially providing insights into the genetic architecture of a crop species after many decades of plant breeding. For example, DNA marker-aided research on long-term artificial selection of oil concentration in the maize kernel reveals that at least 50 genome locations account for about 50% of total genetic variation, which confirms that maize kernel oil content is highly polygenic.[25] This information can be added to the breeder's tool kit

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[24] S. Bout & W. Vermerris (2003) *Molecular Genetics and Genomics* 269:205–214

[25] C.C. Laurie *et al.* (2004) *Genetics* 168:2141–2155

for use in marker-assisted selection to enhance kernel oil content. As a result of such knowledge and available DNA marker tools, a shift toward precision breeding—that is, re-introducing a target gene into a plant under different gene regulation systems, either through marker-assisted selection or direct gene transfer—will be the next step.

NEW CROP USES AND NEW PLANT SPECIES

The choice of a crop species for biofuel production will depend on an ex-ante analysis of energy input-output and environmental impacts. New species should produce more ethanol per unit of feedstock than today's sources (sugarcane in Brazil, maize in the USA, or cassava in Thailand).[26]

Sweet sorghums, which are similar to grain sorghums and have rapid growth, high biomass production, and broader adaptability, have great potential in ethanol production.[27] They produce grain and sugar-rich stalks and have received high priority in some areas of the world, especially the semi-arid tropics, because of their low water requirement, cultivation costs, and environmental benefits, relative to other biofuel crops.

Bio-diesel plantations give another option to restore the self-reliance and economic self-sufficiency in resource-poor rural areas.[28] Non-edible oils from *Jatropha*, *Pongamia*, *Neem*, *Kusum*, and *Pilu* are being advocated. *Pongamia pinnata,* known also as karanja, and *Jatropha curcas,* known as ratanjot, are options for villagers to supplement or replace polluting fuels. They can also provide employment for landless and marginal people. Both *Pongamia* and *Jatropha* can be established in low-rainfall, infertile soils and wastelands, e.g. in some South Asian locations. They are easy to establish, fast growing, hardy, and are not browsed by cattle and goats. When used in blends of up to 20% with diesel (B20), biofuel from these crops requires little or no engine modification. Likewise, the oilcake that is a by-product of oil extraction from these species appears attractive as an organic fertilizer.

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[26] E. Marris (2006) *Nature* 444 :673-676

[27] B.V.S. Reddy *et al.* (2005) *International Sorghum and Millets Newsletter* 46:79–86

[28] S. Wani *et al.* (2006) *Asian Biotechnology and Development Review* 8:11–34

Switchgrass (*Panicum virgatum*) is another plant species posited as a potential biofuel crop.[29] Native to North American prairies, this grass could be the primary perennial species for development as a dedicated cellulosic energy crop. Switchgrass, together with other non-food plant species grown in the USA, could be used to produce over 380 billion liters of biofuel per year, while allowing food, feed, and export demands for other crops to be met, in part because switchgrass grows on lands incapable of supporting traditional food crops. Its cultivation results in 1/8 the nitrogen runoff and 1/100 the soil erosion of food crops. The large root system of switchgrass adds carbon to the soil, instead of depleting it. Breeding programs are aiming at least to double switchgrass yields (currently at about 10 tons per hectare) and increase its ethanol output to about 380 liters per ton, over the mid-term. Recently, a US private plant genomics program to enhance biomass yield with public federal funding announced that its research team was completing the analysis of over 12,000 switchgrass genes and characterizing their genetic variation to speed enhancement of the grass. This effort is part of a large public-private partnership to develop and market new, high-biomass crops for biofuels.

Miscanthus grass species, including those commonly known as Giant Chinese, Silver Grass, Silver Banner Grass, Maiden Grass, and Eulalia Grass, are receiving attention as potential biomass sources for biofuels.[29] Giant *Miscanthus* (*Miscanthus* x *giganteus*) is a hybrid grass that can grow 4 meters high and may be a valuable renewable fuel source. Farmers in Denmark, Great Britain, and Ireland grow *Miscanthus* and use it to produce energy due to its rapid growth, low mineral content, and high biomass yield. About 5,700 liters of ethanol can be produced from the biomass from 0.4 hectares of *Miscanthus*. After harvest, *Miscanthus* can be burned to produce heat and to power turbines. The direct burning of *Miscanthus* stems—a clean-burning fuel—produces only as much carbon dioxide as is removed from the air while they grow, meaning the process is greenhouse-neutral. *Miscanthus* can be mixed with coal in equal amounts to be used in some current coal-burning power plants without modifications.

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[29] K. Sanderson (2006) *Nature* 444: 673–676

CONSERVATION AGRICULTURE AND BIOFUELS

Among other cellulose sources being seriously considered for ethanol production are the crop residues or straws that remain in the field following the harvest of grain crops like maize, rice, and wheat.[30] The continuous removal of crop residues for animal fodder, cooking fuel, and as raw building materials, among other uses, as well as the extensive soil tillage for seeding or for weed control, affect agro-ecosystem sustainability, especially on marginal lands, resulting in extensive soil erosion and loss of soil organic matter, ultimately reducing crop yields. Such degradation also leads farmers to apply increasing levels of inputs, especially fertilizers, to maintain output. Furthermore, the already high and yet increasing production costs faced by many farmers are directly related to the large amounts of fuel used for extensive, mechanical tillage operations. The solution to these and many other problems lies therefore in appropriate conservation agriculture practices, which implies dramatic reductions in tillage or its complete elimination, coupled with the retention of adequate levels of crop residues on the soil surface and, where relevant, diversified and economically viable crop rotations.

In areas such as the southern cone of South America, where farmers have applied conservation agriculture practices such as direct seeding into surface residues on more than 20 million hectares, there have been clear and dramatic reversals in soil degradation and major reductions in production costs; mainly diesel fuel savings associated with the elimination of tillage. By the same token, research at CIMMYT has suggested that zero-tillage without retention of crop residues is not sustainable.

Those who propose using crop residues for biofuels need to take into account the hazards indicated above, especially soil erosion and the depletion of carbon and other nutrients in soils. Crop and system agronomists should be able to tell how much crop residues can be taken off without affecting system sustainability or crop yields, as

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[30] S. Kim & B.E. Dale (2004) *Biomass and Bio-energy* 26:361-375

well as the economical feasibility of removing crop residues, especially if fertilizers are used to replace nutrients. In high-yielding irrigated systems, it may be possible to remove a major portion of crop residues and still retain an adequate level (say, 3-5 tons per hectare) for healthy soils. In rainfed cropping systems, most residues must be retained.

BIOSCIENCE INSTITUTIONAL ARRANGEMENTS FOR BIOFUEL RESEARCH

Clearly, adding biofuel productivity as a target trait brings new research priorities in crop improvement and for managing cropping systems. Multi-purpose crops combining food, feed, fiber, and biofuel traits are needed so that farmers can respond to market changes and reduce or manage risks. It appears that basic crop biofuel research may be better undertaken by academic organizations and the private sector, whereas genetic diversity assessment and "allele mining" could be the main task of public genebanks, particularly those of the CGIAR centers.

We are recently witnessing changes in the nature of public and private sector plant breeding, with the public sector taking on characteristics or roles of the private sector, and vice versa.[31] Public-private partnerships may make effective use of resources by focusing public research on tapping potential plant genetic resources and initial trait genetic enhancement, feeding outputs into public or private breeding programs worldwide. With recent biofuel research and technology advances in the developed world, one role of international public organizations, such as CGIAR centers, will be to foster application of new knowledge and technology among small-scale farmers, particularly in resource-poor areas of the developing world. The CGIAR centers can also bridge gaps in biofuel research, facilitating information sharing and easing access of resource-poor farmers to proprietary technology. One way of achieving the latter is by brokering agreements between the developed world's private sector and potential users in the emerging developing world.

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[31] R.Ortiz & J.H. Crouch (2007) *In* G. Loebenstein & G. Thottappilly (eds.) *Agricultural Research Management*. Springer, Germany. pp. 65-92

WILL BIOFUELS TRANSFORM CROP IMPROVEMENT?

Without a doubt crop biomass itself remains an important breeding target, and this trait benefits from ongoing genetic enhancement of yield potential and stability, as well as by crop betterment for stress-prone environments. With the advent of new genomic tools, basic research on cell wall and starch chemistry will allow new comparative biology undertakings. Among other outcomes, these should bring important knowledge from research-endowed crops to improve less-researched crops or plant species that have bio-energy potential.

Energy-saving agriculture, include zero-tillage and use of insect-resistant or weed-suppressing crops, will have a role in addressing current energy concerns. Researchers should tackle the energy-budget for agriculture at a global scale, as well as finding means to reduce waste in agriculture and food chains or to exploit waste as a biofuel source. For example, bio-nitrification inhibition can reduce production costs and the environmental impacts of intensive agriculture, especially when some available estimates of costs of crop biofuels are based on the assumption of the continuous use of high input agriculture.

The current use of grains as a biofuel source will move to more cellulosic ethanol[32] and then finally to the use of lignin, which is the most abundant plant biological material. Such a switch in raw materials provides an opportunity for the application of "green" genetic modification technology, which may be more easily accepted by society than current products of agricultural genetic engineering, especially if the aim is a transgenic bio-energy (rather than food) crop grown in a marginal area. Likewise, engineering microbes for biomass processing will be an important contribution to cheaper ethanol.[33], [34] In short, a new mind-set for producing biofuels through a socially responsible, systems biology approach should be pursued.

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[32] D. Kennedy (2006) *Science* 316:515

[33] H. Alper (2006) *Science* 314:1565–1568

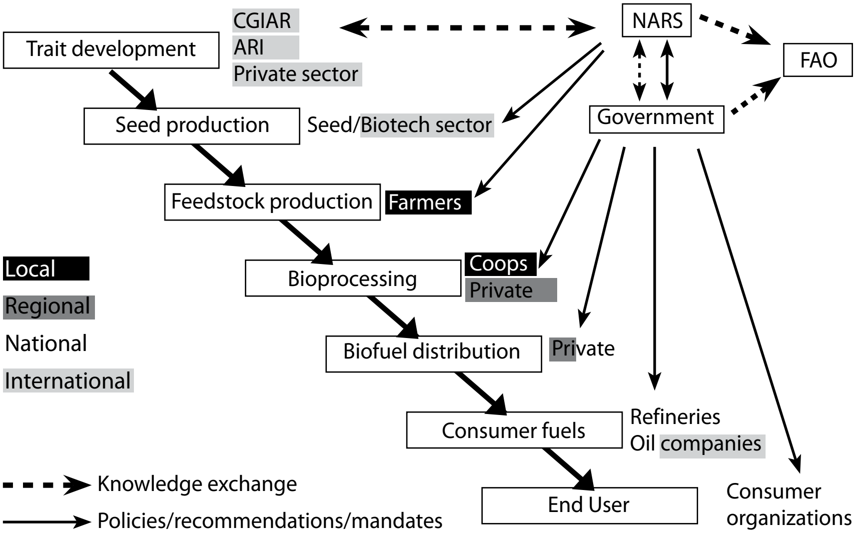
[34] G. Stephanopoulos (2007) *Science* 315 :801–804

A HOLISTIC, KNOWLEDGE-BASED BIOFUEL AGENDA

A knowledge-based research agenda on biofuels should focus on socio-economics and policy, crop and natural resource management, species selection, and germplasm enhancement. The identification of researchable issues should follow a value-chain approach and with partners throughout as indicated below:

Socio-economics and policy research must address the factors underlying feedstock supplies, demand side factors, and opportunities for global trade in feed stocks or biofuels for the developing world. Likewise, research will include the assessment of biofuel production in industrialized nations and potential negative food security impacts in the developing world. Expected outputs include:

- Impacts on commodity prices, the environment, food security, hunger, and poverty.[35]
- Scenario research to target favorable environments for biofuel production.



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[35] A.K. Chandel (2007) *Biotechnology and Molecular Biology Review* 2 :14-32

- Ex-ante biofuel trait analysis to guide both crop genetic enhancement and natural resource management.
- A value-chain bio-energy research approach to benefit the rural poor.
- Examining the role of biofuels in climate change mitigation policies, and designing small- or large-scale biofuel systems to be climate-proof or resilient in areas that are likely to undergo increasing environmental stress.[36] For example, biofuel combustion is the largest source of black carbon emissions in India, and its control may mitigate climate change South Asia.[37],[38]
- Intellectual property management for non-food or feed use of plant genetic resources.

Conservation agriculture practices will be an important component of crop and natural resource management research, since residue removal contributes to water runoff, soil erosion, and, through a loss of soil organic matter, long-term degradation.[39] Agronomists need therefore to define the minimum thresholds of crop residues for sustainable production in particular farming systems, especially in low-yield rainfed areas. Hence, this research agenda needs to address:

- Energy balances in different farming environments and technologies.
- Crop, crop residues and biofuel feedstock in high and low potential farming.
- The bio-energy balance: inputs (including water productivity) and outputs.[40]
- Potential biofuel feedstocks from intensive cropping and systems and livestock.

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[36] H. Von Blottnitz & M.A. Curran (2007) *Journal of Cleaner Production*. In press.

[37] J. Lelieveld *et al.* (2001) *Science* 291–296

[38] C. Venkataraman *et al.* (2005) *Science* 307: 1454–1456

[39] R. Lal & D. Pimentel (2006) *Soil Tillage* 93 :237-238

[40] T.D. Patzek *et al.* (2005) Environment, Development and Sustainability 7:319–336

- The potential of using invasive species (e.g. *Prosopis juliflora* in drylands)[41] for bio-energy.
- The need for environmentally-sustainable first- and second-generation biofuel conversion technologies and feedstocks; e.g., dried distillers grains with solubles.[42]

Last but not least, crop genetic enhancement will aim to develop high-density cellulose-biomass multi-crops, with easy breakdown for biofuel conversion, and with high photosynthesis and metabolism, thereby resulting in more input-use efficient plants. Likewise, biofuel crops should show resilience to stressful environments—that is, yield stability—especially if marginal environments are used for biofuel crops.[43], [44], [45] In this regard the research agenda for species selection and genetic resource enhancement needs to undertake:

- Comparative analysis of crops and trees for efficient energy extraction and use.
- Allele discovery in gene banks for biofuel traits.
- Molecular breeding for biofuel crops.
- Incorporation or introgression of wild resources by re-thinking selection for sink allocation and bringing the perennial and biofuel traits into today's annual crops.
- Genetic enhancement of biofuel crops aiming at rainfed marginal or non-agricultural environments and exploring other plant options for bio-energy.

PUBLIC-PRIVATE-PARTNERSHIPS FOR MULTI-USE PLANTS TO BENEFIT THE POOR

Partnerships should refine and apply new paradigms to generate and access research results. They should also bring innovations in institutional arrangements for investigating a technology to

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[41] S. Raghu *et al*. (2006) *Science* 313:1742

[42] A.K. Rosentrater (2006) *Ecology and Society* 11(1):http://www.ecologyandsociety.org/vol11/iss1/ resp2/

[43] D. Tilman *et al.* (2006) *Science* 314:1598–1599

[44] M.P. Russelle (2007) *Science* 316:1567b DOI: 10.1126/science.1139388

[45] D. Tilman *et al.* (2007) *Science* 316:1567c DOI: 10.1126/science.1140365

sustainably meet emerging societal energy needs. This is what Prof. Chris Somerville (Stanford University, California) calls a new, mission-oriented “Manhattan Project” in the USA for accelerated development of the cellulosic-based biofuel industry.[46] In the developing world, the priority for this partnership will be to fill the gap in biofuel product development, aiming to benefit small- to medium-scale farmers and to improve rural livelihoods. This public-private partnership should also provide tools for governments to assess national biofuel potential and to enact enabling policy frameworks and incentive structures. In the process, such a partnership should generate a global knowledge network throughout biofuel value chains to link farmers and consumers to markets and empower them.

Trait discovery in genebanks will be an important activity. The private sector has to identify, as per their research on biomass conversion, new traits needed in feedstock sources. Changes in plant architecture are envisaged, since future bio-energy crops may look quite distinct from today’s available types. One expected change may be the potential conversion from annual to perennial growth habit, which may also re-shape agroecosystems in some crop biofuel-producing areas.

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[47] R. Ortiz *et al.* (2006) *Vision 2020 for Food Agriculture and the Environment – Bio-energy and Agriculture: Promises and Challenges* 14:7

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