

Biofuels and ecoagriculture: can bioenergy production enhance landscape-scale ecosystem conservation and local livelihoods?

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Introduction

The term “biofuel” refers to any energy source derived from recently living plants, animals, or their byproducts. For thousands of years, humans have used traditional biofuels such as wood, charcoal, and dung to cook, heat, and manufacture goods. In the early 20th century, liquid biofuels began to be used as transport fuel, and, in fact, ethanol and vegetable oil were originally envisioned as the fuel sources for the combustion and diesel engines. In recent decades, biofuels have become regionally important sources of electricity and liquid transport fuels in some parts of the world, while traditional biofuels continue to provide 70-97% of all energy in African nations and in many rural parts of Asia (Ramachandra et al. 2004, Kgathi & Zhou 1995). In short, the production, processing, and use of biofuels is both local and global, small-scale and large-scale, subsistence and commercial—and we believe that dialogues on biofuels should reflect these many forms.

Recent dialogue around biofuels, stimulated by its rapidly growing attractiveness as an alternative to fossil fuels throughout the world, however, has tended to focus on large-scale bioenergy production to supply the global market for liquid fuels, and analyses have tended to be national to global in scale. For example, previous environmental analysis around biofuels has focused on global issues such as pressure for land conversion, water use, and global climate change. Discussions on livelihood implications have tended to be similarly broad. While broad policy questions—such as whether liquid biofuels should replace a significant amount of petroleum in the global energy mix or whether national and international laws and market incentives should favor biofuel production—should indeed be analyzed at a global scale, the important questions of where and how to produce biofuels are better considered at smaller scales where the importance of agricultural landscapes for ecosystem services and livelihoods can be more clearly evaluated. It is the landscape scale, after all, where investment and management decisions often take place.

A focus on landscape analysis is appropriate for any major new crop introduction with high land and water resource needs. The difference in the current proliferation of biofuel crops and trees is the sheer pace and scale of new investment, largely driven by consumers and traders who live outside the anticipated production areas, and engaging energy sector actors who have not previously been involved in agriculture. These circumstances require that particular care is taken as the industry develops. This moment is a strategic and brief opportunity to shape biofuels development in ways that will support the kinds of agricultural landscapes needed to provide essential food security, livelihoods and ecosystem services in the 21st century—and to integrate sustainable energy needs fully and on a large scale into multifunctional landscapes.

Accordingly, this paper seeks to supplement existing global analyses by exploring how the design and management of biofuel production and processing systems at local to landscape scales affects their environmental, economic, and social outcomes. In particular, the paper

identifies those landscape contexts, production practices, and types of investments that have the best chance of delivering benefits while avoiding negative aspects associated with biofuel production. In addition, in contrast to previous work analyzing biofuels in the context of large-scale production and global markets, our perspective focuses especially on small farmers and rural communities as producers of biofuel. The paper also considers the social and environmental impacts of large-scale bioenergy production on small producers and low-income populations in developing countries.

We propose an increased emphasis on biofuel production systems that promote landscape multifunctionality by simultaneously delivering energy production, rural livelihood benefits, biodiversity conservation, and a wide range of ecosystem services. These goals are consistent with the framework of “ecoagriculture,” which we define below and within which we situate this analysis (McNeely & Scherr 2003).

The paper begins by defining ecoagriculture as a framework for agricultural management, landscape planning, and the evaluation of biofuel production systems. We then present a typology of biofuel production systems, using three typical systems as examples. Next, we synthesize scientific findings and experience to date to propose criteria for landscape design incorporating biofuel production systems, followed by national and global policy, market, and technological innovations that could support biofuel production consistent with the principles of ecoagriculture. We conclude with a summary of recommendations and areas for further analysis.

Ecoagriculture as a framework for analysis

Ecoagriculture is an approach to managing agricultural landscapes so that they simultaneously provide three key outcomes: 1) conservation of native biodiversity and ecosystem services, 2) production of agricultural or silvicultural goods (including bioenergy products) on a sustainable basis, and 3) viable livelihoods for local people (McNeely & Scherr 2003). Ecoagriculture approaches are especially needed in places where biodiversity conservation, production, and livelihoods are all important goals, and where competition for land demands solutions that increase the synergies among these objectives. Ecoagriculture provides a useful framework within which to analyze bioenergy production systems and to design effective strategies for bioenergy development that support all three goals.

Ecoagriculture is fundamentally a landscape approach based on understanding and intentionally managing the inter-relations among different parts of an agricultural mosaic landscape, including cropped areas, grasslands, natural forest patches and reserves, and aquatic resources. A mosaic arrangement of such land uses can not only provide diversified income sources and conserve native biodiversity, but also maximize the production of ecosystem services that sustain agricultural productivity such as pollination, water purification, and soil fertility enhancement.

Bioenergy production—like the concept of ecoagriculture—is beginning to blur the boundaries between production systems traditionally viewed as separate, ranging from annual crops and crop residues to diversified perennial systems to biomass harvest from managed natural areas. The opportunities for such integrated biofuels ecosystems will increase immensely when cellulosic technologies utilizing native grass and tree species become established. Such technologies are already at the pilot phase and many experts expect them to be widely implemented within five years.

Yet, current trajectories in biofuel development point in a different direction. Growers and investors have favored vast monocultures over diversified and integrated systems that rely

on and replenish natural capital. Table 1 presents key differences between industrial production models and a diversified production system based on the principles of ecoagriculture.

Table 1. Divergent potentials of biofuel production, processing, and marketing in relation to the goals of ecoagriculture.

Diversified ecoagriculture system	Industrial monoculture production model
Conservation of biodiversity and ecosystem services	
Diverse biofuel production systems—especially perennial grassland and tree-based systems—increase landscape heterogeneity and provide plant and wildlife habitats	Monoculture production systems provide little value for native biodiversity
Small-scale biofuel production provides a viable substitute for firewood, reducing pressure on natural forests	Biofuel production competes with food production, increasing pressure to deforest additional land for agriculture
Biofuel feedstocks consist of native species that require no irrigation and little fertilizer, thus maintaining water quality and quantity	Water- and chemical-intensive production of corn, soybeans, and other feedstocks depletes surface and groundwater sources and contributes to water pollution
Perennial biofuel crops restore soil organic carbon stocks and provide long-term carbon sequestration (Tilman et al. 2006, Sartori et al. 2006, Lemus & Lal 2005)	Intensive annual and perennial cropping systems sequester little carbon; clearing of native vegetation to install biofuel plantations yields net emissions of greenhouse gases (cite Indonesia peatlands clearing)
Production	
Biofuels production areas contribute ecosystem services that help support nearby food crop areas	Biofuel crops require high levels of inputs including water, fertilizers, and pesticides that degrade surrounding land
Strategic planting of perennial biofuel crops on degraded land restores soil fertility, improving future crop production potentials	Overt time soil erodes and organic carbon levels decrease, reducing future potential
Rural livelihoods	
Biofuel crops are incorporated into small farms, increasing diversification and providing an additional revenue source	Biofuel crops are grown on dedicated farms for which income is totally dependent on sale of a single energy crop
Local or cooperative biofuel processing facilities capture most of the value of feedstocks, increasing income in rural areas	Producers sell feedstocks to consolidated processing facilities, with profits accruing to outside corporations
Creation of distributed, small-scale energy systems in rural areas increases energy security and reduces dependence on dirty, labor-intensive traditional biomass fuels	Bioenergy feedstocks are processed into liquid transportation fuels destined for middle- and high-income consumers, often in other countries; local small farmers are unable to afford or use these fuels

Diversified ecoagriculture system	Industrial monoculture production model
Payment for ecosystem services (PES) programs may compensate farmers for positive environmental externalities associated with biofuel production, such as carbon sequestration and habitat creation	Biofuel production generates negative environmental externalities such as deforestation and water pollution, which create regulatory and perception risks for agribusiness

Toward a typology for evaluating biofuels production in ecoagriculture landscapes

The concept of ecoagriculture can be used as a framework for developing typologies of bioenergy production systems. As a point of departure for this analysis, we develop a typology based on ecoagriculture concepts to be evaluated on two primary axes—with associated ‘sub-axes’—upon which any system (current or future) could be plotted:

Axis 1: Ecological characteristics of feedstock production. This axis examines the biodiversity and ecosystem services implications of the production system. These depend heavily on the type of feedstock and the way that the production system is integrated into an agricultural landscape in an ecologically balanced way. From this perspective, there would be a large differentiation between a chemical-intensive monoculture on one end vs. a perennial polyculture, integrated agroforestry system, or semi-natural grasslands on the other. Sub-axes of ecosystem services could include carbon stocks, soil fertility, hydrological function, biodiversity levels and other ecological indices.

Axis 2: Social and market characteristics of the supply chain. Central to this measure is the relative benefit of biofuels production for local farmers vs. other actors in a supply chain. Sub-axes would include the user of the bioenergy product (farmer’s community vs. international market); the biofuel’s efficiency benefit relative to the energy product being replaced (community biogas for cooking needs to be evaluated as an alternative to firewood); the implications for the farmer of trade-offs between energy and food crops; and the scale of the bioenergy system (small, decentralized pathways vs. industrial pathways fully integrated into global market have very different implications for the distribution of benefits). These questions get to the heart of the political economy issues that will come to the fore as the biofuels industry rapidly expands.

Using these axes as a framework for analysis, we can begin to develop a typology for biofuels from an ecoagriculture perspective. We consider three cases: smallholder production of bioenergy feedstocks for local use and small-scale income generation; smallholder production at a commercial level for national or international markets; and medium- and large-scale commercial production for national and international markets.

System 1: Smallholder production for local use and small-scale income generation

Objectives: Local fuel availability (fuel security), potential for income generation through an additional cash crop.

Axis 1: In this system, the biofuel feedstock is produced on small farms and processed in on-site or nearby small-scale processing facilities to generate electricity, biogas, or possibly liquid

biofuels. Biofuel production could consist of small plots dedicated to annual or perennial energy crops, biofuel production in interstitial spaces in the landscape, or biofuel production as part of integrated land use systems such as agroforestry. Because biofuel production occurs on many small plots in conjunction with other agricultural and non-agricultural land uses, the overall landscape heterogeneity is likely to be high. If well designed, biofuel production areas within these landscape mosaics could provide other valuable benefits as well, such as windbreaks, restoration of degraded production areas, habitats for native biodiversity, and a range of ecosystem services. Thus, of the three types of systems considered here, these smallholder systems have the best chance of contributing to multifunctional landscape management. In addition, small farmers who produce their own food (along with their fuel) will raise a far greater diversity of crops than if they were producing a necessarily homogenous commodity for a far away market. This diversity is likely to offer protection against pests, disease, crop failure, and commodity price fluctuations.

Axis 2: The most obvious benefit of this system, perhaps, is that many poor rural people will gain access to an inexpensive and sustainable source of energy. With local production and marketing, the feedstock producer will receive much, if not all, of the financial benefit from production. In contrast to systems 2 and 3, there will be little opportunity or incentive for outside actors to interfere with or exploit the producers. Furthermore, because the feedstock is bound only for local markets, prices may be shielded from fluctuations in international markets.

Further research is needed to assess the benefits and drawbacks of replacing traditional biomass fuels such as firewood, charcoal, dung, and crop residues with locally produced biogas and electricity. However, in many landscapes, this conversion would free up two scarce resources: 1) labor that is currently required to search for fuelwood in locations where it is scarce; and 2) biomass such as crop residues and dung, which could play an important role in restoring soil fertility were it not used to meet domestic energy needs. In addition, moving away from traditional “dirty” biomass fuels could ameliorate domestic indoor air quality and the health problems associated with it.

System 2: Smallholder commercial production for national or international market

Objective: Maximum cash income for small farmers.

Axis 1: Like system 1, these systems will be based on small patches and will therefore have the potential to provide the biodiversity and ecosystem service benefits described above. While ecologically diverse interstitial spaces will provide ecosystem benefits regardless of the on-farm production systems, economic pressures from commercial markets may cause farmers to reduce on-farm diversity and eliminate these uncropped areas. Useful parallels may be drawn from the experiences of outgrower schemes for products such as sugar cane and pulp wood. In these cases, large buyers and processors provide planting materials and production guidelines to smallholder growers. The result is often a high level of landscape homogeneity. However, there may also be opportunities to productively utilize marginal lands or existing degraded lands, especially if they are managed sustainably in ways that build up soils and use water efficiently.

Axis 2: The benefit to local people in this case will depend on their negotiating power and the efficiency of transportation systems. Without these biofuels could just reinforce existing spatial

inequalities. The tradeoff between food and fuel is also confronted most directly here for small farmers who have historically grown their own food. These producers will be at the mercy of external markets if they transition away from food crops (or biofuel crops) for local consumption to biofuel feedstock production for external markets. If these markets crash they will likely face serious food shortages. There are obvious benefits to farmers of using biofuels to diversify their sources of income.

There are, however, benefits of biofuel over food crops. They tend to carry lower production risks and greater adaptability to drought periods than many food crops. Nonperishability also allows farmers the option of selling at anytime of year when they can get the best price. But such benefits are maximized with a diversified biofuel/food system, not a wholesale shift away from food crops. It may be necessary to establish rules limiting the scale and proportion of monocultures in the landscape to ensure that land is left for left for food and nature.

System 3: Large and medium scale commercial production for national and international market

Objective: Maximize profits for large and medium-sized actors by producing feedstocks on relatively large tracts of land.

Axis 1: Given current circumstances and trends, system 3 landscapes will almost certainly be ecologically bankrupt, monoculture systems of sugar, corn, soybeans, or palm oil. In this context, the two major issues from an ecological perspective are ‘what is this system replacing?’ and ‘is there anything that can be done to make these systems more sustainable?’

If the system is replacing another large monocrop, the ecological implication will be neutral, but economic pressures may also push production into previously forested or otherwise ecologically sensitive areas. This seems to be happening with soybeans in the Amazon and oil palm in Indonesia.

Efforts are underway to explore more sustainable systems for the dominant biofuel crops including the Sustainable Oil Palm roundtable. There is also potential to enhance the sustainability and diversity of sugar and corn systems through rotations (*Clay 2004*). For corn, conservation tillage and plant breeding could reduce impacts. A huge leap in sustainability of large tracts of biofuels would be a transition away from annual to perennial crops. (see section below on cellulosic future). Additionally, there is potential to utilize woodlots for biofuels.

Axis 2: In type 3, political economy issues are at the forefront. A danger in these systems is that as higher prices for biofuels create financial incentives for larger scales of production, smaller actors may be marginalized and protected areas opened for production. In some cases, the best working agricultural land, or large tracts of land that was previously community land, will be annexed by governments for their own use, or on behalf of large companies. For example, increasing prices for sugar and oil palm are driving degazetting of the last remaining fragments of protected forests in Uganda

Farm and landscape scale: issues of design

As suggested above, bioenergy production can be part of a strategy for diversified land use to achieve multiple objectives at landscape scale; similarly, it can contribute to a diversified financial strategy for rural households and communities. For this to happen, however, will require careful landscape planning based on local data and scientific analysis used in the service of stakeholders' goals. Key decisions include siting of biofuel production areas, selection of energy crops, farm and landscape configuration, and integration versus segregation of crops and land uses. Some design considerations related to landscape configuration, biodiversity management, and soil fertility are discussed below.

Spatial heterogeneity: Numerous studies point to the importance of habitat heterogeneity in sustaining both alpha (within-site) and gamma (landscape-wide) species diversity. Vertical structure mimicking natural habitat types can provide the multiple habitat niches that support a diversity of native bird, insect, and mammal species. Horizontal structure increases the number of habitat niches across the landscape, and especially in relatively uniform agricultural systems the introduction of natural and semi-natural habitat patches can greatly increase conservation value (Christian et al. 1998, Blann 2006).

As technologies for processing cellulose improve, it is expected that multiple woody and grass species will be viable feedstocks, allowing for diversified multi-strata vegetational communities to function as bioenergy "plantations." Even in the absence of such technology, bioenergy crops can be incorporated into multistrata agroforestry systems that also provide a variety of food crops. On larger farms, planting and harvesting efficiency will need to be balanced against the conservation benefits of spatially heterogeneous systems.

Biodiversity conservation: Several studies reveal that perennial grass and short-rotation woody biomass crops can improve habitat relative to agricultural crops (Roth et al. 2005, Murray et al. 2003, Semere & Slater 2007). For these crops, the timing of harvests may be critical. In some cases, management strategies benefiting biodiversity would not diminish yield at all. For example, grasses and trees could be harvested in rotations so that animal populations have a shifting mosaic of habitats with some viable refugia at all times. However, short-rotation perennial crops are unlikely to sustain many forest species, and are not a substitute for viable forest patches and reserves in landscapes where forest is the native land cover type (Christian et al. 1998).

Soil fertility and soil carbon: One of the most promising win-win opportunities is the use of biofuel crops to help restore soil fertility and soil carbon on degraded lands. Several recent studies indicate that perennial grass mixtures and short-rotation woody crops grown for biofuel can sequester up to three tons of carbon per hectare per year (Tilman et al. 2006, Sartori et al. 2006, Lemus & Lal 2005). Thus, if these feedstocks are processed with minimal fossil fuel inputs, they actually become carbon negative fuel sources. Of perhaps greater importance for small farmers in degraded landscapes, such systems can help restore soil fertility by retaining organic matter and nutrients in the soil. Furthermore, bioenergy crops may reduce the need for energy currently obtained from crop residues and dung; freeing up these natural organic fertilizers will reduce soil degradation on nearby plots (Lal 2006).

Many of these factors are illustrated in existing bioenergy cropping systems in different parts of the world. Examples include:

- Harvest of biomass from grasslands as a way of maintaining the financial viability of extensive production systems in parts of Europe
- Producing biodiesel for local energy use from *Jatropha* in India and West Africa enhancing habitat value
- Raising native mixed grasses in the American Midwest as a replacement of monoculture cornfields
- Brazilian farmers growing sugar in rotation with tomatoes, soya, peanuts and other food crops

National and global scale: issues of policy and technology

The ability of biofuel producers to make the decisions necessary to create and manage systems featuring these ideal characteristics will hinge on whether an enabling environment can be created by supportive policy and technological development. Many of the critical decisions that will guide the development of the industry are already in the formulation process.

Policy issues

Several countries, including the USA, the EU member states and Brazil, have developed policies to increase the usage of biomass and biofuels in their existing energy mix. Biofuels are heavily subsidized throughout the developed world, including the European Union and the USA, because they are more expensive to produce than conventional fossil fuels (at current prices).

Some examples of these policies include:

- The 2003 European Union Biofuels Directive. EU members will be encouraged to produce a quarter of transportation fuels from biomass by 2030. The EU has established a goal of 5.75% biofuels in the fuel transport. Much of this demand will be met with inputs from other countries, primarily in the tropics. For example, Indonesia and Malaysia are expected to be major suppliers, especially of palm oil.
- The US programme on alternative fuels. As dictated by the US Energy Policy Act of 2005, the USA aims to replace 30% of its transportation fuel with biofuel by 2030. This policy, like the EU case, will stimulate production in the tropics to meet demand.
- Brazil is a leader in the development of biofuel, and plans to allocate more agricultural lands for biomass production are under way. Brazil and the United States are building a new partnership to expand the use of ethanol and biofuels throughout Latin America and the Caribbean in an effort to increase energy security and create rural jobs for poorer nations.

As these policies and other develop, their implications will require careful consideration. The macro-level, financial incentives and alternative fuel mandates at the national level will create incentives for biofuel production in the tropics. These countries do not currently have the regulatory and governance frameworks to ensure that supplies are grown in a sustainable

manner. Importing countries should work them to develop these frameworks to promote ecological production and also to ensure that the incentives they create for large scale production do not marginalize small farmers. Regulations could delineate where and how feedstocks can be planted to ensure that large scale production stays in areas that have already been in large holdings or had been previously unsettled. Secure land tenure in importing countries will help small farmers reap more of the benefits of this new market. Criteria and indicators could be developed for certification of biodiversity/watershed/farmer-friendly biofuels production.

Technology development: the cellulosic future

As cellulosic technologies develop, the diversity of crops that can be used as biofuel feedstock will greatly expand. This will have an enormous impact on each type of production discussed. Perhaps the most important implication from an ecological perspective will be the potential for a transition from annual to perennial crops. For example, areas around the world currently under large scale grain production might transition to large tracts of mixed native grasses that would not only be a sustainable feedstock for biofuels production, but would also sequester carbon in roots and surrounding soil. In this way biofuels production could actually help stabilize ecosystems. These technological advances could also turn certain hardy landscape-reclaiming trees into feedstocks. This development would thus create a new financial incentive to plant trees in heavily degraded areas and could have enormous positive implications for struggling farmers and pastoralists in drylands throughout the world.

Before these new feedstocks become useable for biofuels production, however, a critical technological factor will be the development of machinery with the capacity to process a diversity of feedstocks, thus creating the potential for a diversified landscape of biofuel crops.

Conclusions

As the demand for biofuels rapidly expands, its associated production systems and supply chains are forming and consolidating. There is now a moment of opportunity when these systems may still be malleable and forward-thinking management could significantly enhance ecological sustainability and livelihood development, particularly for poor farmers in the developing world.

We suggest the approach of ecoagriculture as a set of principles to guide thinking on the future of biofuels. There is enormous potential for biofuels to be integrated into multi-functional landscapes that can sustain production, ecosystem services, biodiversity and local livelihoods. Ideal mosaic landscapes would feature a mix food crops with deep-rooted biofuel crops, such as prairie grasses and fast-growing trees. These systems could reduce land degradation, enhance biodiversity habitat, sequester carbon, increase water infiltration and retention, and use fewer fertilizers and pesticides. These design characteristics would be accompanied by a supply chain that maximized benefits for farmers.

Developing a typology based on this ecoagriculture vision, we presented three general cases and concluded that *Smallholder production for local use and small-scale income generation* has the greatest potential to sustain production and supply chain systems consistent with these ideals. The other two cases *Smallholder commercial production for national or international market* and *Large and medium scale commercial production for national and international market* could certainly support ecoagriculture landscapes, particularly when cellulosic technologies become widely available, but they will need to be very carefully guided

by far-sighted management, including regulatory and possibly certification systems, based on appropriate ecological and political scales.

This initial discussion certainly leaves many questions unanswered and leads the way to further research and analysis. A starting point would be to more systematically document cases, including the ones briefly mentioned in this paper, of biofuel production landscapes achieving the goals of ecoagriculture. This process will certainly inform what has been in many ways a theoretical exercise. Related experiences, particularly those in outgrowing and collective buying from high biomass production systems will also be useful. A further step will be to engage producers themselves to further ascertain how the academic and policy discussions around biofuels can best inform their decisions.

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