Energy Returns on Ethanol Production
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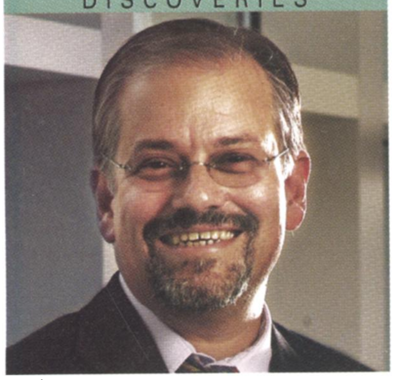
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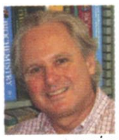
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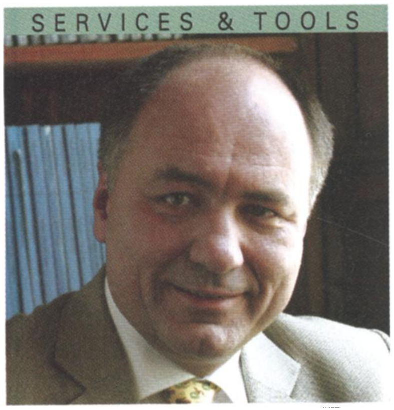
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Reference
1. Much of this evidence comes from results of U.S. Department of Agriculture (USDA) Crop Development Center, Land Grant Institution, and U.S. Department of Energy– and USDA-funded research.

Energy Returns on Ethanol Production

IN THEIR REPORT "ETHANOL CAN CONTRIBUTE to energy and environmental goals" (27 Jan., p. 506), A. E. Farrell *et al.* focus in part on whether biomass-derived ethanol fuel delivers positive net energy [i.e., whether energy return on energy invested (EROI) exceeds 1:1; see (*1*)]. Their analysis neither resolves nor clarifies the fundamental issues that make net energy important and contentious. First, in their comparison of ethanol and gasoline, they confuse EROI—a productivity index—with the energy efficiency of an oil refinery. Second, their use of energy break-even as a litmus test is a red herring; it is more crucial that EROI is high compared with competing energy sources. Exploration for domestic petroleum in the 1930s returned 100 Joules for each Joule invested; the EROI for oil production today is ~15:1 (*2*). Because the present EROI of fossil fuels is high, the ~90 net Quads (1 Quad = ~1 exajoule) delivered annually to the U.S. economy results from an investment of only about 10 Quads (*2*). To provide that same 90 net Quads from corn-derived ethanol would require an investment of 145 to 500 Quads (based on an EROI = ~1.6:1 to 1.2:1, implied by Farrell *et al.*'s fig. 1). The current transportation system cannot be maintained on a fuel system delivering only a 1.6:1 return. Third, the focus on petroleum inputs is too limited. Natural gas is often the principal input to biomass fuel production, but its future is no more certain than oil's; we already import more than 15% of what we use (*3*). Fourth, the authors ignore the energy cost of repairing soil erosion.

Finally, the one (speculative) result for an energy technology based on cellulose in fig. 1 implies an EROI of ~50:1. This (very uncertain) EROI indicates that this source of biomass could be potentially useful, but ethanol from corn remains too marginal to survive without heavy economic subsidy.

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1. C. J. Cleveland, R. Costanza, C. A. S. Hall, R. Kaufmann, *Science* **225**, 890 (1984).
2. C. J. Cleveland, *Energy* **30**, 769 (2005).
3. Official U.S. Energy Information Web page, eia.doe.gov.

IN THEIR REPORT "ETHANOL CAN CONTRIBUTE to energy and environmental goals" (27 Jan., p. 506), A. E. Farrell and colleagues offer hopeful opinions about corn-based ethanol. Their analysis suggests that, since the ratio of ethanol produced to fossil fuel used is positive, ethanol should be further developed. If replacing oil is our goal, we must look at two parameters of this approach: (i) energy return on investment (EROI) including environmental impacts on soil, water, climate change, ecosystem services, etc.; and (ii) scalability and timing. Farrell and colleagues' most optimistic EROI of 1.2:1 (which does not include tractors, labor, or environmental impacts) implies that we need to produce 6 MJ of ethanol to net 1 MJ of energy for other endeavors. Thus, the yield of ethanol would not be 360 gallons per acre gross yield, but rather a mere 60 gallons per acre net yield, not even two fill-ups for an SUV. The entire state of Iowa, if planted in corn, would yield approximately five days of gasoline alternative.

To devote half the nation's corn crop to ethanol would require an input of 3.42 billion barrels of oil (almost half our current national use) to net 684 million barrels of "new" ethanol energy. We would also lose food and soil nutrients, suffer ecosystem damage, and use massive amounts of water for irrigation.

We need alternative energy. But ethanol from corn is neither scalable nor sustainable. Let's pursue better options.

NATHAN HAGENS, ROBERT COSTANZA, KENNETH MULDER

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IN THEIR REPORT "ETHANOL CAN CONTRIBUTE to energy and environmental goals" (27 Jan., p. 506), A. E. Farrell *et al.* address the energy balance and greenhouse gas (GHG) emissions of ethanol from corn and show the pessimistic analysis of these issues by Pimentel and Patzek (*1*) to be wrong. Pimentel and Patzek are also wrong in their analysis of cellulose-derived ethanol.

Hammershlag's (*2*) estimates for the energy return per nonrenewable energy invested for near-term cellulosic ethanol technology range from 4.4:1 to 6.6:1, and Farrell *et al.* calculate a value of 8.3:1. The energy return for mature cellulosic ethanol technology is expected to be over 10:1 (*3*). Pimentel and Patzek estimate the energy return for cellulosic ethanol at 0.69:1. Why such a striking discrepancy? The primary reason is that Pimentel and Patzek estimate the externally supplied processing energy to be over 25 MJ/liter ethanol, whereas in all other studies this value is zero, since it is met by lignin from cellulosic biomass.

Whether energy return and greenhouse gas emissions of ethanol production are favorable depends on how the process is configured and designed. The fact that Pimentel and Patzek's process does not have positive energy returns should not be used to measure the potential of this promising energy path.

The science is clear; it's time to move on from the energy balance debate and focus on policies that encourage the greatest oil savings and reductions in greenhouse gas emissions from both corn and cellulosic ethanol.

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2. R. Hammershlag, *Environ. Sci. Technol.*, in press.
3. N. Greene *et al.*, Growing Energy, www.nrdc.org/air/energy/biofuels/contents.asp (2004).

THE METHODOLOGICAL FLAWS IN A. E. FARRELL *et al.*'s Report "Ethanol can contribute to energy and environmental goals" (27 Jan., p. 506) are revealed in the authors' fig. 1b, which shows that motor gasoline has a negative net energy and the highest input/output ratio, while ethanol technologies have positive net energies and lower input/output ratios. These numbers imply that motor gasoline is the marginal fuel seeking to displace biomass fuels.

This contradiction is caused by inconsistencies in the boundaries that are used to analyze their energy balance. For motor gasoline, the authors add the energy content of the gasoline to the effort used to produce it. The energy used to produce motor gasoline is much less than its energy content —estimates for the total energy input/energy output ratio are about 0.06 (*1*).

For biomass fuels, the authors report only the petroleum input/output ratio. Other fuels used in the process should also be included; these cannot be assumed to be sustainable (as exemplified by natural gas shortages) The biomass fuels are not used as liquids—(much of the co-products are used to generate electricity), which also needs to be taken into account. Including these additional fuels raises the input/output ratio to 0.79 (ethanol today) or 0.82 (CO_2 intensive). If the U.S. economy used oil with an energy input/output ratio of about 0.8, the energy equivalent of about 80 million barrels per day of oil would be used to generate the 20 million barrels per day of refined petroleum products that the United States uses outside of the oil sector.

Once the boundaries are made equivalent, motor gasoline has a much higher energy surplus and a lower energy input/energy out ratio than biomass fuels. This result matches the economic reality described by the authors' first paragraph—biomass fuels, not motor gasoline, need subsidies and tax breaks.

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Reference

1. C. J. Cleveland, *Energy* **30** (no. 5), 769 (2005).

IN THE NET-ENERGY ANALYSIS IN THEIR REPORT "Ethanol can contribute to energy and environmental goals" (27 Jan., p. 506), A. E. Farrell *et al.* do not (i) define the system boundaries, (ii) conserve mass, and, consequently, (iii) conserve energy. Most of the current First Law net-energy models of the industrial corn-ethanol cycle are based on nonphysical assumptions and should be discarded.

When properly formulated, mass and First Law energy balances of corn fields and ethanol refineries account for the photosynthetic energy, some of the environment restoration work, and the co-product energy (*1*). These show that production of ethanol from corn is two to four times less favorable than production of gasoline from petroleum. From thermodynamics, it also follows that the ecological devastation wrought by industrial biofuel production must be severe. With the DDGS coproduct energy credit, 3.9 gallons of ethanol displace on average the energy in 1 gallon of gasoline. Without the DDGS energy credit, this average number is 6.2 gallons of ethanol. Equivalent CO_2 emissions from the corn ethanol cycle are 50% higher than those from gasoline and become 100% higher if methane emissions from cows fed with DDGS are accounted for.

The U.S. ethanol industry has consistently inflated its ethanol yields by counting 5 volume percent of #14 gasoline denaturant (8% of energy) as ethanol. Also, imports from Brazil and longer chain alcohols seem to have been counted as U.S. ethanol (*1*). A detailed statistical analysis of 401 corn hybrids from Illinois reveals that the highest possible yield of ethanol is 2.64 ± 0.05 (SD) gallons EtOH/bu (*1*). The commonly accepted U.S. Department of Agriculture estimate of mean ethanol yield in the United States, 2.682 gallons EtOH/bu (*2*), is one standard deviation above this estimate.

TAD W. PATZEK

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References and Notes

1. The detailed calculations and arguments can be found at http://petroleum.berkeley.edu/patzek/BiofuelQA/Materials/RealFuelCycles-Web.pdf.
2. H. Shapouri, P. Gallagher, M. S. Graboski, USDA's 1998 Ethanol Cost-of-Production Survey, Agricultural Economic Report No. 808 (U.S. Department of Agriculture, Economic Research Service, Office of Energy and New Uses, Washington, DC, 2002).

Response

WE THANK THE LETTER AUTHORS FOR THEIR comments. As Lynd *et al.* and Cleveland *et al.* point out, the potential benefits of cellulosic ethanol technologies would include a shift away from intensely farmed monocultures such as corn and positive effects on soil erosion, fertilizer runoff, and biodiversity. In addition, because cellulosic technologies can use a wide variety of feedstocks, their flexibility may allow for more applications worldwide. Similarly, we agree with Hagens *et al.* and Patzek that we need more sustainable processes than current corn ethanol production.

However, Hagens *et al.* are mistaken that our analysis excludes tractors or labor; these were included. And Cleveland *et al.* and Kaufmann incorrectly state that we ignored natural gas or coal inputs. These are explicitly included in the ERG Biofuels Analysis Meta-Model (EBAMM, cells N6, N28, N30, N37 and N38 in worksheet "Net Energy") (*1*).

We agree with Hagens *et al.*, Cleveland *et al.*, and Patzek that meaningful measurement of environmental impacts is critical to an appropriate evaluation of biofuels. However, including incommensurable quantities such as soil erosion and climate change into a single metric requires an arbitrary determination of their relative value. We stressed the advantages of individual metrics for petroleum consumption and greenhouse gas emissions and encouraged the development of specific metrics for environmental effects such as soil erosion. In addition to exposing trade-offs among competing objectives, multiple metrics permit more focused analysis and help reduce uncertainty (see related correction on page 1748).

Hagens *et al.*, Cleveland *et al.*, and Kaufmann incorrectly assert that our paper focused on energy return on investment (EROI). The Supporting Online Material explains why ratios such as EROI are methodologically inferior to the additive metric we use (*1*). Even a quality-adjusted EROI is a single metric that has the problems noted above. Furthermore, such aggregation can lead to mischaracterizations. For example, Hagens *et al.* inappropriately label total energy input into ethanol production as gasoline or petroleum, even though it is predominantly coal and natural gas.

Patzek's Letter is based on a non–peer-reviewed online document that has changed several times since its receipt. Nonetheless, much of his analysis appears to be rigorous in detail but erroneous overall. For instance, extractable starch only applies to wet milling, which presently produces approximately 30% of U.S. ethanol. Almost all new ethanol plants are dry mills, for which total fermentable starch is a better measure of ethanol yield, and that yield at least 5% more ethanol per unit mass of corn than wet milling (*2*, *3*). Further, Patzek arbitrarily assumes that spreading co-product animal feed on agricultural land is the best way to maintain soil quality, ignoring among other things the potential of alternative cropping systems (*4*).

These Letters focus on different questions than did our paper. EROI measures the efficiency of primary energy production, but is not useful for comparing different ways of using fossil energy resources to create liquid transportation fuels, which was the point of our paper (*1*). Life-cycle assessments such as ours are not designed to balance mass and energy; they are designed to evaluate environmental implications of the production, use, and disposal of products and fuels.

In retrospect, we should have labeled our metric not as net energy value (NEV) but as Fossil Energy Value (FEV), which, following, is calculated as FEV = $E_{out} - (F_F + P_F)$, where E_{out} is the energy content in the delivered fuel, F_F is primary fossil energy in feedstocks, and P_F is the primary fossil input energy in non-feedstocks (*5*). For biomass, F_F is zero, which explains the seeming inconsistency in system boundaries that Kaufmann reports (*2*). The system boundaries of EBAMM are clearly defined in Equations S-1 through S-7, even if not explicitly labeled as such.

Like the Letter authors, we believe that ethanol can contribute to energy and environmental goals only as part of an overall strategy that also includes more efficient vehicles, other sustainable energy sources, and careful monitoring of ethanol production. The magnitude and timing of this contribution will depend on the development of better methods of producing ethanol than today's corn-based approach. To encourage these changes, we should measure what we care about—greenhouse gas emissions and soil erosion, for example—and provide strong incentives to ethanol producers to improve their performance in these areas. A close reading of our paper and supporting material reveals far more agreement among us all than these Letters suggest.

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2. S. Butzen, D. Haefele, P. Hilliard, *Crop Insights* **13**, 1 (2003).
3. H. Shapouri, P. W. Gallagher, "2002 Ethanol Cost-of-Production Survey" (U.S. Department of Agriculture, Washington, DC, 2003).
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CORRECTIONS AND CLARIFICATIONS

News of the Week: "Court revives Georgia sticker case" by C. Holden (2 June, p. 1292). The article incorrectly characterizes the Discovery Institute in Seattle, Washington, as a think tank for the creationist movement. The institute is a public policy organization that operates many different programs, including the Center for Science & Culture, which supports the work of scholars who explore challenges to evolution and promote the concept of intelligent design.

News of the Week: "RU-486–linked deaths open debate about risky bacteria" by J. Couzin (19 May, p. 986). The story mistakenly implied that a woman's risk of death from a *Clostridium sordellii* infection after a nonsurgical abortion is about 1 in 100,000. In fact, this is the estimated risk of contracting a *C. sordellii* infection following a nonsurgical abortion; to date, the infections are invariably fatal.

Reports: "Ethanol can contribute to energy and environmental goals" by A. E. Farrell *et al.* (27 Jan. 2006, p. 506). Michael Wang of Argonne National Laboratory has raised interesting and important issues associated with greenhouse gas (GHG) emissions from corn (maize) ethanol production in this Report. The U.S. Department of Agriculture (USDA) confirmed that the data reported for lime application had been calculated incorrectly and kindly updated these values. The custom report and an updated version of the Supporting Online Material that discusses the issues raised in this erratum in more detail are downloadable from http://rael.berkeley.edu/EBAMM. The corrected data are expected to be available on the USDA Web site in the coming months. In conducting a reanalysis, even larger uncertainties were discovered in the emissions factor of lime and the emission factor for nitrous oxide (N_2O) resulting from nitrogen fertilizer application. With these refinements, the *Ethanol Today* case now yields a point estimate of net greenhouse gases for corn ethanol at 18% below conventional gasoline, very close to the initially reported value of 15% below gasoline, but with an expanded uncertainty band of –36% to +29%.

TECHNICAL COMMENT ABSTRACTS

COMMENT ON "Nature of Phosphorus Limitation in the Ultraoligotrophic Eastern Mediterranean"

Michelle S. Hale and Richard B. Rivkin

Thingstad *et al.* (Reports, 12 August 2005, p. 1068) reported that in situ mesoscale phosphorus enrichment of the eastern Mediterranean Sea altered selected biological parameters and concluded that the added phosphorus was rapidly transferred from bacteria to mesozooplankton. However, because of a lack of replication and a misinterpretation of their statistical analyses, that conclusion is not supported by the data.

Full text at www.sciencemag.org/cgi/content/full/312/5781/1748c

RESPONSE TO COMMENT ON "Nature of Phosphorus Limitation in the Ultraoligotrophic Eastern Mediterranean"

T. F. Thingstad, C. S. Law, M. D. Krom, R. F. C. Mantoura, P. Pitta, S. Psarra, F. Rassoulzadegan, T. Tanaka, P. Wassmann, C. Wexels Riser, T. Zohary

With no requirement for synoptic treated (IN) and control (OUT) stations, analysis of covariance is an interesting statistical technique for testing IN-OUT differences in Lagrangian experiments, but it has inherent limitations due to its assumption of linear responses. With this limitation properly considered, we find that analysis of covariance strengthens, not weakens, experimental support for the food-web transfer mechanisms we proposed.

Full text at www.sciencemag.org/cgi/content/full/312/5781/1748d

Caution on Nominee to Head USGS

IN THE NEWSMAKERS ITEM "NEW USGS HEAD" (19 May, p. 995) on the nomination of Mark Myers to head the U.S. Geological Survey (USGS), I was quoted by the writer Erik Stokstad as saying that Myers "has a significant amount of integrity." I have no direct knowledge of Myers and therefore have no basis for evaluating his fitness for the job. However, his background is in such contrast to previous USGS directors that I said to Stokstad that Congress must ask some very tough questions of Myers before confirming him.

As I said to Stokstad, because of the Bush Administration's history of interfering with the integrity of science conducted at agencies and of being overly friendly to the oil and gas industry, Congress should demand full answers from Myers regarding his view on the independence of the government's main science agency and whether he would stand up to an administration that has shown no qualms about dismissing good science when it conflicts with political goals.

KAREN WAYLAND

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Letters to the Editor

Letters (~300 words) discuss material published in *Science* in the previous 6 months or issues of general interest. They can be submitted through the Web (www.submit2science.org) or by regular mail (1200 New York Ave., NW, Washington, DC 20005, USA). Letters are not acknowledged upon receipt, nor are authors generally consulted before publication. Whether published in full or in part, letters are subject to editing for clarity and space.