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Carbon-Negative Biofuels from Low-Input High-Diversity Grassland Biomass

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Biofuels derived from low-input high-diversity (LIHD) mixtures of native grassland perennials can provide more usable energy, greater greenhouse gas reductions, and less agrichemical pollution per hectare than can corn grain ethanol or soybean biodiesel. High-diversity grasslands had increasingly higher bioenergy yields that were 238% greater than monoculture yields after a decade. LIHD biofuels are carbon negative because net ecosystem carbon dioxide sequestration (4.4 megagram hectare^{-1} year^{-1} of carbon dioxide in soil and roots) exceeds fossil carbon dioxide release during biofuel production (0.32 megagram hectare^{-1} year^{-1}). Moreover, LIHD biofuels can be produced on agriculturally degraded lands and thus need to neither displace food production nor cause loss of biodiversity via habitat destruction.

Globally escalating demands for both food (*1*) and energy (*2*) have raised concerns about the potential for food-based biofuels to be sustainable, abundant, and environmentally beneficial energy sources. Current biofuel production competes for fertile land with food production, increases pollution from fertilizers and pesticides, and threatens biodiversity when natural lands are converted to biofuel production. The two major classes of biomass for biofuel production recognized to date are monoculture crops grown on fertile soils (such as corn, soybeans, oilseed rape, switchgrass, sugarcane, willow, and hybrid poplar) (*3*–*6*) and waste biomass (such as straw, corn stover, and waste wood) (*7*–*9*). Here, we show the potential for a third major source of biofuel biomass, high-diversity mixtures of plants grown with low inputs on agriculturally degraded land, to address such concerns.

We performed an experiment on agriculturally degraded and abandoned nitrogen-poor sandy soil. We determined bioenergy production and ecosystem carbon sequestration in 152 plots, planted in 1994, containing various combinations of 1, 2, 4, 8, or 16 perennial herbaceous grassland species (table S1) (*10*). Species composition of each plot was determined by random draw from a pool of species. Plots were unfertilized, irrigated only during establishment, and otherwise grown with low inputs (*10*). The 16-species plots are the highest diversity, or the LIHD (low-input, high-diversity), treatment. All plots were burned in early spring to remove aboveground biomass before growth began. Soil samples, collected before planting in 1994 and again in 2004, determined carbon sequestration in soil. Plots were sampled annually from 1996 to 2005 for aboveground biomass production.

Annual production of aboveground bioenergy (i.e., biomass yield multiplied by energy released upon combustion) (*10*) was an approximate log function of planted species number (Fig. 1A). On average for the last 3 years of the experiment (2003–2005), 2-, 4-, 8-, and 16-species plots produced 84%, 100%, 157%, and 238% more bioenergy, respectively, than did plots planted with single species. In a repeated measures multivariate analysis of variance, annual bioenergy production was positively dependent on the number of planted species ($F_{1,\ 155} = 68.4$, $P < 0.0001$), on time ($F_{9,\ 147} = 8.81$, $P < 0.0001$), and on a positive time-by-species number interaction ($F_{9,\ 147} = 11.3$, $P < 0.0001$). The interaction occurred because bioenergy production increased more through time in LIHD treatments than in monocultures and low-diversity treatments, as shown by the ratio of bioenergy in LIHD (16 species) plots to those in 8-, 4-, 2-, and 1-species plots (Fig. 1B).

The gross bioenergy yield from LIHD plots was 68.1 GJ ha^{-1} year^{-1}. Fossil energy needed for biomass production, harvest, and transport to a biofuel production facility was estimated at 4.0 GJ ha^{-1} year^{-1} (table S2). Different biofuel production methods capture different proportions of bioenergy in deliverable, usable forms (Fig. 2) (*10*). Cocombustion of degraded land LIHD biomass with coal in existing coal-fired electric generation facilities would provide a net gain of about 18.1 GJ ha^{-1} as electricity (*11*). Converting LIHD biomass into cellulosic ethanol and electricity is estimated to net 17.8 GJ ha^{-1} (*12*). Conversion into gasoline and diesel synfuels and electricity via integrated gasification and combined cycle technology with Fischer-Tropsch hydrocarbon synthesis (IGCC-FT) is estimated to net 28.4 GJ ha^{-1} (*10*, *13*). In contrast, net energy gains from corn and soybeans from fertile agricultural soils are 18.8 GJ ha^{-1} for corn grain ethanol and 14.4 GJ ha^{-1} for soybean biodiesel (*14*). Thus, LIHD biomass converted via IGCC-FT yields 51% more usable energy per hectare from degraded infertile land than does corn grain ethanol from fertile soils. This higher net energy gain results from (i) low-energy inputs in LIHD biomass production because the crop is perennial and is neither cultivated, treated with herbicides, nor irrigated once established and likely requires only phosphorus replacement fertilization because nitrogen is provided by legumes; (ii) the more than 200% higher bioenergy yield associated with high crop biodiversity; and (iii) the use of all aboveground biomass, rather than just seed, for energy. LIHD biofuels also provide much greater net energy outputs per unit of fossil fuel input than do current biofuels [net energy balance (NEB) ratios of Fig. 2]. Fertile lands yield about 50% more LIHD biomass (and bioenergy) than our degraded soils (*15*, *16*).

Annual carbon storage in soil was a log function of plant species number (Fig. 1C). For 1994–2004, there was no significant net sequestration of atmospheric CO_2 in monoculture plots [mean net release of CO_2 of 0.48 ± 0.44 Mg ha^{-1} year^{-1} (mean ± SE)], but, in LIHD plots, there was significant soil sequestration of CO_2 (2.7 ± 0.29 Mg ha^{-1} year^{-1}). Soil carbon storage occurred even though all aboveground biomass-based organic matter was removed annually via burning. Periodic resampling of soils in a series of prairie-like agriculturally degraded fields found C storage rates similar to those of the LIHD treatment and suggested that this rate could be maintained for a century (*17*). The observed annual rate of change in soil C at a particular soil depth declined with depth ($P = 0.035$), suggesting that an additional 5% more

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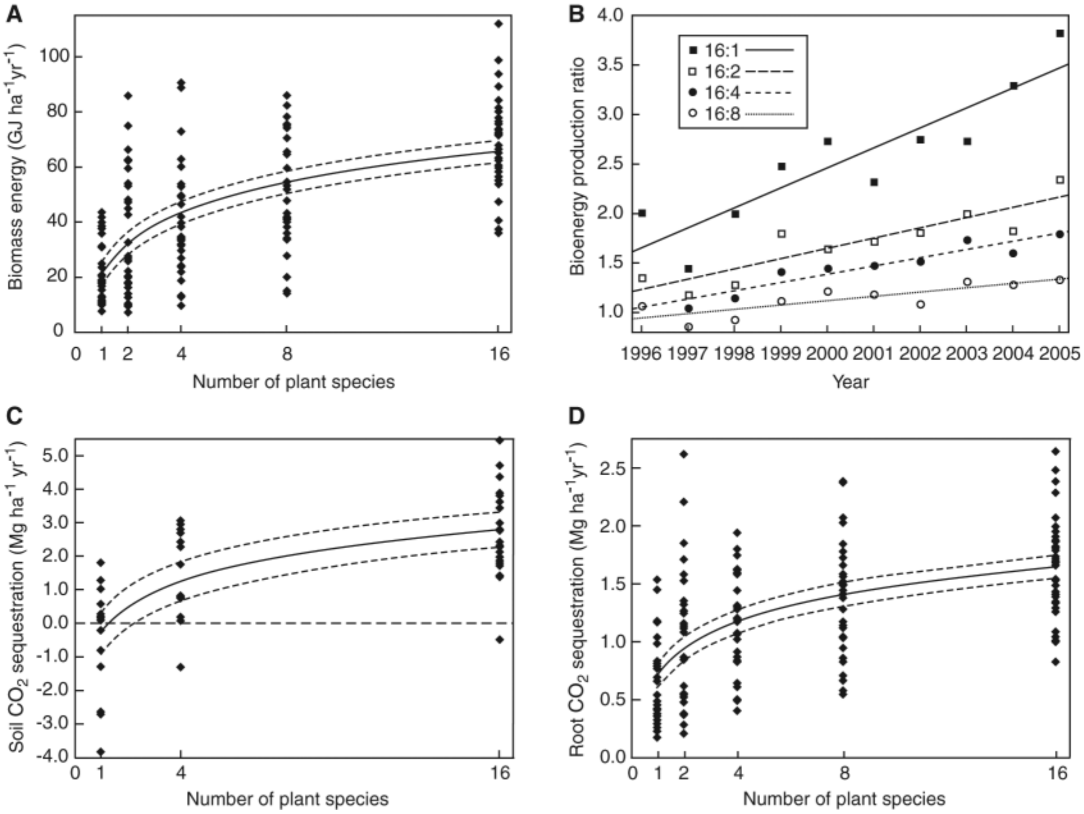

Fig. 1. Effects of plant diversity on biomass energy yield and CO_2 sequestration for low-input perennial grasslands. (**A**) Gross energy content of harvested aboveground biomass (2003–2005 plot averages) increases with plant species number. (**B**) Ratio of mean biomass energy production of 16-species (LIHD) treatment to means of each lower diversity treatment. Diverse plots became increasingly more productive over time. (**C**) Annual net increase in soil organic carbon (expressed as mass of CO_2 sequestered in upper 60 cm of soil) increases with plant diversity as does (**D**) annual net sequestration of atmospheric carbon (as mass of CO_2) in roots of perennial plant species. Solid curved lines are log fits; dashed curved lines give 95% confidence intervals for these fits.

C may be stored in soils deeper than we measured (below 60 cm depth).

In 2004, after 10 years of growth, atmospheric CO_2 sequestration in roots was a log function of plant species numbers (Fig. 1D). On an annual basis, 0.62 Mg ha^{-1} $year^{-1}$ of atmospheric CO_2 was sequestered in roots of species grown in monocultures, and 160% more CO_2 (1.7 Mg ha^{-1} $year^{-1}$) was captured in roots of 16-species plots. Multiple regression showed that root CO_2 sequestration (Mg ha^{-1} of CO_2) increased as a log function of plant species number (S), as a log function of time ($Year$), and their interaction $\{C_{\mathrm{root}} = -1.47 + 6.16\log_{10}(S) + 9.64\log_{10}(Year) + 9.60[\log_{10}(S) - 0.613][\log_{10}(Year) - 0.782]$ where $Year = 3$ for 1997, the first time roots were sampled; overall $F_{3,\ 1260} = 191$, $P < 0.0001$; for $\log_{10}(S)$, $F_{1,\ 1260} = 398$, $P < 0.0001$; for $Year$, $F_{1,\ 1260} = 148$, $P = 0.0001$; for $S \times Year$, $F_{1,\ 1260} = 27.3$, $P = 0.0001\}$. This regression suggests that most root carbon storage occurred in the first decade of growth; during the second decade, roots of 16-species plots are projected to store just 22% of C stored during the first decade. Measurements at greater depths in 10 LIHD plots suggest that 43% more C may be stored in roots between 30 and 100 cm.

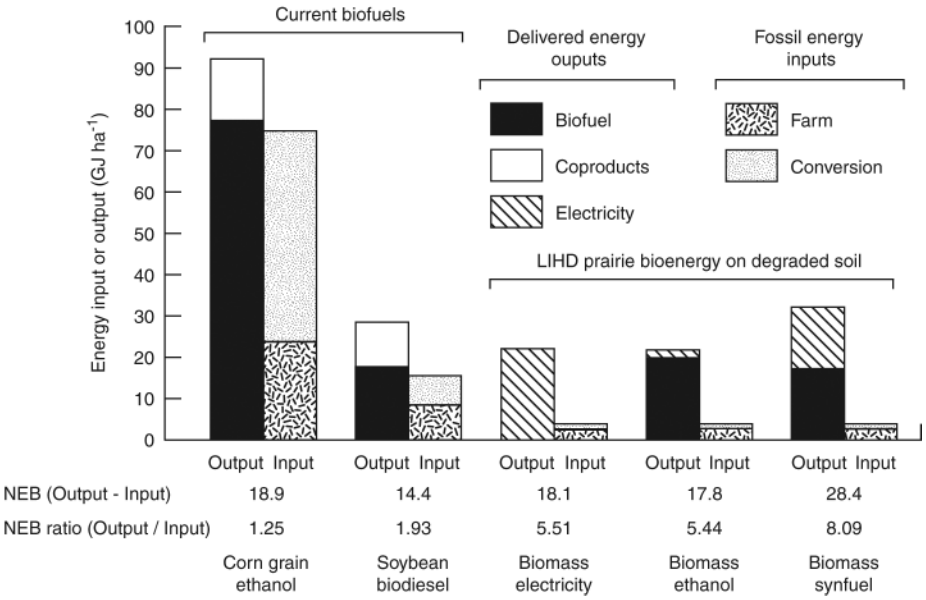

Fig. 2. NEB for two food-based biofuels (current biofuels) grown on fertile soils and for LIHD biofuels from agriculturally degraded soil. NEB is the sum of all energy outputs (including coproducts) minus the sum of fossil energy inputs. NEB ratio is the sum of energy outputs divided by the sum of fossil energy inputs. Estimates for corn grain ethanol and soybean biodiesel are from (*14*).

LIHD plots had a total CO_2 sequestration rate of 4.4 Mg ha^{-1} $year^{-1}$ in soil and roots during the decade of observation. Trends suggest that this rate might decline to about 3.3 Mg ha^{-1} $year^{-1}$ during the second decade because of slower root mass accumulation. In contrast, the annual rate of CO_2 sequestration for monocultures was 0.14 Mg ha^{-1} $year^{-1}$ for the first decade and projected to be indistinguishable from zero for subsequent decades.

Across their full life cycles, biofuels can be carbon neutral [no net effect on atmospheric CO_2 and other greenhouse gases (GHG)], carbon negative (net reduction in GHG), or carbon sources (net increase in GHG), depending on both how much CO_2 and other greenhouse gases, expressed as CO_2 equivalents, are removed from or released into the atmosphere during crop growth and how much fossil CO_2 is released in biofuel production. Both corn ethanol and soybean biodiesel are net carbon sources but do have 12% and 41% lower net GHG emissions, respectively, than combustion of the gasoline and diesel they displace (*14*). In contrast, LIHD biofuels are carbon negative, leading to net sequestration of atmospheric CO_2 across the full life cycle of biofuel production and combustion (table S3). LIHD biomass removed and sequestered more atmospheric CO_2 than was released from fossil fuel combustion during agriculture, transportation, and processing (0.32 Mg ha^{-1} year^{-1} of CO_2), with net life cycle sequestration of 4.1 Mg ha^{-1} year^{-1} of CO_2 for the first decade and an estimated 2.7 to 3 Mg ha^{-1} year^{-1} for subsequent decades. GHG reductions from use of LIHD biofuels in lieu of gasoline and diesel fuel are from 6 to 16 times greater than those from use of corn grain ethanol and soybean biodiesel in lieu of fossil fuels (Fig. 3A).

LIHD biofuel production should be sustainable with low inputs of agrichemicals, as in our study. Legumes in LIHD plots can supply nitrogen (*18*). In our experiment, total soil nitrogen of LIHD plots increased 24.5% ($P < 0.001$) from 1994–2004, but monoculture total soil nitrogen was unchanged ($P = 0.83$). However, some amount of N fertilization may be useful in dry habitats that lack efficient N-fixing species. Application of P or other nutrients may be needed if initially limiting or to replace nutrient exports (Fig. 3B). Production may be sustainable with low pesticide use, because plant disease incidence and invasion by exotic species are low in high-diversity plant mixtures (Fig. 3C) (*19*).

Switchgrass (*Panicum virgatum*), which is being developed as a perennial bioenergy crop, was included in our experiment. Switchgrass monocultures can be highly productive on fertile soils, especially with application of pesticides and fertilizer (*20*, *21*). However, on our infertile soils, switchgrass monoculture bioenergy [23.0 ± 2.4 GJ ha^{-1} year^{-1} (mean ± SE)] was indistinguishable from mean bioenergy of monocultures of all other species (22.7 ± 2.7 GJ ha^{-1} year^{-1}) and yielded just a third of the energy of LIHD plots (*10*).

How much energy might LIHD biomass potentially provide? For a rough global estimate, consider that about 5 × 10^8 ha of agriculturally abandoned and degraded land producing biomass at 90 GJ ha^{-1} year^{-1} (*22*) could provide, via IGCC-FT, about 13% of global petroleum consumption for transportation and 19% of global electricity consumption (*2*). Without accounting for ecosystem CO_2 sequestration, this could eliminate 15% of current global CO_2 emissions, providing one of seven CO_2 reduction "wedges" needed to stabilize global CO_2 (*23*). GHG benefits would be larger if LIHD biofuels were, in general, carbon negative, as might be expected if late-successional native plant species were used in LIHD biomass production on degraded soils [e.g., (*17*)].

The doubling of global demand for food and energy predicted for the coming 50 years (*1*, *2*) and the accelerating use of food crops for biofuels have raised concerns about biodiversity loss if extant native ecosystems are converted to meet demand for both food and biofuels. There are also concerns about environmental impacts of agrichemical pollution from biofuel production and about climate change from fossil fuel combustion (*14*, *24*–*26*). Because LIHD biomass can be produced on abandoned agricultural lands, LIHD biofuels need neither compete for fertile soils with food production nor encourage ecosystem destruction. LIHD biomass can produce carbon-negative biofuels and can reduce agrichemical use compared with food-based biofuels. Moreover, LIHD ecosystem management may provide other ecosystem services, including stable production of energy, renewal of soil fertility, cleaner ground and surface waters, wildlife habitat, and recreation (*18*, *19*, *24*, *27*, *28*). We suggest that the potential for biofuel production and carbon sequestration via low inputs and high plant diversity be explored more widely.

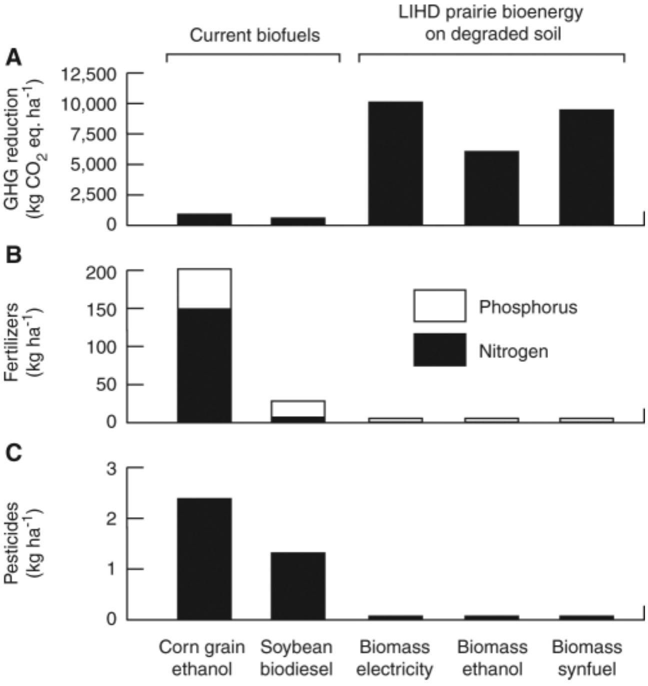

Fig. 3. Environmental effects of bioenergy sources. (**A**) GHG reduction for complete life cycles from biofuel production through combustion, representing reduction relative to emissions from combustion of fossil fuels for which a biofuel substitutes. (**B**) Fertilizer and (**C**) pesticide application rates are U.S. averages for corn and soybeans (*29*). For LIHD biomass, application rates are based on analyses of table S2 (*10*).

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