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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 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 (i) low-energy inputs in LIHD biomass production because the crop is perennial and is not dependent on the number of planted species and (ii) 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 CO2 in monoculture plots [mean net release of CO2 of 0.48 ± 0.44 Mg ha−1 year−1 (mean ± SE); but, in LIHD plots, there was significant soil sequestration of CO2 (2.7 ± 0.29 Mg ha−1 year−1)]. Soil carbon storage occurred even at 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
C may be stored in soils deeper than we measured (below 60 cm depth).

In 2004, after 10 years of growth, atmospheric CO2 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 CO2 was sequestered in roots of species grown in monocultures, and 160% more CO2 (1.7 Mg ha$^{-1}$ year$^{-1}$) was captured in roots of 16-species plots. Multiple regression showed that root CO2 sequestration (Mg ha$^{-1}$ of CO2) increased as a log function of plant species number ($S$), as a log function of time (Year), and their interaction:

$$C_{\text{root}} = -1.47 + 6.16\log_{10}(S) + 9.64\log_{10}(\text{Year}) + 9.60\log_{10}(S) - 0.613\log_{10}(\text{Year}) - 0.782$$

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 $S \times \text{Year}, F_{1, 1260} = 27.3, P = 0.0001$. 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.

LIHD plots had a total CO2 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 CO2 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 CO2 and other greenhouse gases (GHG)], carbon negative (net reduction in GHG), or carbon sources (net increase in GHG), depending on both how much CO2 and other greenhouse gases, expressed as CO2 equivalents, are removed from or released into the atmosphere.

**Fig. 1.** Effects of plant diversity on biomass energy yield and CO2 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 CO2 sequestered in upper 60 cm of soil) increases with plant diversity as does (D) annual net sequestration of atmospheric carbon (as mass of CO2) in roots of perennial plant species. Solid curved lines are log fits; dashed curved lines give 95% confidence intervals for these fits.

**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).
during crop growth and how much fossil CO₂ 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 CO₂ across the full life cycle of biofuel production and combustion (table S3). LIHD biomass removed and sequestered more atmospheric CO₂ than was released from fossil fuel combustion during agriculture, transportation, and processing (0.32 Mg ha⁻¹ year⁻¹ of CO₂), with net life cycle sequestration of 4.1 Mg ha⁻¹ year⁻¹ of CO₂ 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 biofuel potentially provide? For a rough global estimate, consider that about 5 × 10⁸ ha of agriculturally abandoned and degraded land producing biofuel 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 CO₂ sequestration, this could eliminate 15% of current global CO₂ emissions, providing one of seven CO₂ reduction "wedges" needed to stabilize global CO₂ (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 for biofuels have raised concerns about biodiversity loss if extant native ecosystems are or encouraged to stabilize global CO₂ (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)].

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).