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Response to Comment on “Carbon-Negative Biofuels from Low-Input High-Diversity Grassland Biomass”

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We discovered that biofuels from low-input high-diversity mixtures of native perennial prairie plants grown on degraded soil can provide similar bioenergy gains and greater greenhouse gas benefits than current corn ethanol produced from crops grown in monoculture on fertile soil with high inputs. Russelle *et al.*'s technical concerns are refuted by a substantial body of research on prairie ecosystems and managed perennial grasslands.

Russelle *et al.* (1) raise several technical concerns that lead them to question our conclusions about the energetic and environmental advantages of biofuels derived from diverse mixtures of native perennial prairie plant species over biofuels from high-input annual food crops such as corn (2). The nature of their comments suggests that research results well known in ecology may be less familiar to those outside the discipline. Indeed, our approach stands in marked contrast to that of conventional high-input agriculture. Each of their concerns, addressed below, is refuted by published studies of the ecology of high-diversity grasslands, and none of them has substantive effect on our original conclusions.

Russelle *et al.* (1) question the ability of low-input high-diversity (LIHD) prairie biomass to grow sustainably with low nutrient inputs. U.S. corn, in contrast, requires substantial inputs: 148 kg/ha of nitrogen, 23 kg/ha of phosphorus, and 50 kg/ha of potassium annually (3). Leaching and erosional nutrient losses are much lower for perennial grasslands than for annually tilled row crops such as corn; hence, much lower inputs are needed. Moreover, we recommended harvesting prairie biomass when senescent in late autumn because this would “both yield greater biomass and decrease ecosystem loss of N, P, and other nutrients” [supporting online material for (4)]. Replacing nutrients removed by harvesting would require about 4 kg/ha of P and 6 kg/ha of K, should they be limiting (5, 6). LIHD mixtures needed no N fertilization because N fixation by legumes more than compensated for N exports in harvested biomass. Also, unlike some cultivated legumes, our native legumes grow well and fix N on acidic soils without liming (7). Moreover, several studies have shown that biomass yields of high-diversity grasslands are

sustainable with low inputs. Annual hay yields from high-diversity Kansas prairie (8) showed no declines over 55 years despite no fertilization. Similarly, hay yields increased slightly during 150 years of twice-annual biomass removal in high-diversity unfertilized plots of the Park Grass experiment (9, 10). In total, nutrient inputs sufficient to sustain LIHD biomass production are an order of magnitude lower than for corn.

We showed that the dense root mass of LIHD prairie led to high rates of soil carbon sequestration (2). Russelle *et al.* (1) express concern that fire may have caused carbon storage through charcoal formation. However, published studies show that annual accumulation of charcoal carbon in frequently burned grasslands was <1% of our observed rate of soil carbon accumulation (11, 12). Similarly, fire had no effect on soil black carbon levels in a 6-year study of mixed-grass savanna (13). The concern about effects of late autumn mowing versus burning is also unfounded. Annual mowing and burning have similar effects on prairie biomass production (14, 15), and mowing does not cause prairie yields to decrease (8).

We proposed using mixtures of native prairie perennials for biofuels in part because, contrary to the assertion of Russelle *et al.* (1), such mixtures are easily established and require low or no inputs for maintenance. Indeed, prairie readily reestablishes itself from seed and displaces exotic plant species during natural succession on many degraded agricultural lands in the Great Plains (16). Prairie restoration, such as on the 6000 ha restored recently in Minnesota by The Nature Conservancy, is performed using agricultural machinery, not manual labor as Russelle *et al.* suggest. Our hand-weeding was done to maintain monoculture and low-diversity treatments. In contrast, the LIHD treatment led to rapid competitive displacement of exotic weedy and pasture species. LIHD plots were strikingly resistant to subsequent plant invasion and disease (17, 18). In portions of LIHD plots for which weeding had been stopped for 3 years, only 1.7% of total biomass came from invaders,

which themselves were mainly native prairie perennials, and this invasion did not impact energy production.

Our one-sentence “rough global estimate” of the energy LIHD biomass might potentially provide was brief, but well-supported and conservative. As to our estimated land base, 9×10^8 ha of global agricultural lands have been degraded so as to have “great reductions” in agricultural productivity, and an additional 3×10^8 ha are “severely degraded” and offer no agricultural utility (19, 20). A review of 17 studies found a median value of 7.1×10^8 ha of degraded land available globally for biofuel production (21). Our suggestion of 5×10^8 ha is 30% lower and is therefore a conservative estimate.

In our experiment (2), severely degraded land planted to LIHD mixtures had biomass production that was 46% as much as its native biome, temperate grassland (22). To be conservative, we assumed that LIHD mixtures of native species planted on degraded land would produce 20% less than we observed, i.e., just 37% of the average of its native biome (22). Weighting this LIHD production estimate by the global area for each biome produced our estimate of $90 \text{ GJ ha}^{-1} \text{ year}^{-1}$ globally and of degraded lands potentially providing—through the integrated gasification combined cycle (IGCC)/Fischer-Tropsch process—about one-seventh of the global transportation and electricity demand. We stand by that estimate. Further, we urge that the energy and carbon sequestration potential of low-input high-diversity mixtures of locally native plant species be explored for degraded lands around the world.

Our energy accounting was thorough and correct. We reported actual energy balances for U.S. corn ethanol and soybean biodiesel as currently produced (both of which cause net increases in greenhouse gases), and we compared them to three ways that LIHD prairie biomass might be used to produce carbon-negative biofuels (i.e., biofuels that, in total for their life cycle, decrease greenhouse gas levels). We showed that these new carbon-negative biofuels could provide similar or greater net energy gains per hectare than current biofuels.

The concerns of Russelle *et al.* (1) are refuted by a thorough consideration of the published literature. As to current biofuels, we agree that the energy and greenhouse gas benefits of corn ethanol could be improved, but we disagree about methods. First, burning the high-protein co-product of corn ethanol production to power ethanol production facilities, as Russelle *et al.* suggest, seems unwise because greater protein production is required to meet global nutritional needs. Burning this protein is not an industry standard, nor is it discussed in any recent ethanol energy balance reviews (23, 24). Second, harvest and use of corn stover (the senescent stalks and leaves of corn plants) to power ethanol plants would likely cause soil organic

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carbon levels to fall, and increase both carbon dioxide release and soil erosion. A better alternative would be powering corn ethanol plants with LIHD biomass, likely by gasification. If done properly, the ethanol produced could be carbon-neutral and have a markedly higher net energy gain than current corn ethanol.

The world's energy and climate problems are likely to be solved only by a combination of approaches and technologies, including wind and solar energy, increased energy efficiency, and renewable biofuels (25). Our research found that biofuels from LIHD biomass grown on degraded lands have substantial energy and greenhouse gas advantages over current U.S. biofuels. Moreover, LIHD production of renewable energy on agriculturally marginal lands could help ameliorate what might otherwise be an escalating conflict between food production, bioenergy production, and preservation of the world's re-

maining natural ecosystems. LIHD biofuels merit further exploration.

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