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GREENHOUSE GAS EMISSIONS FROM BIO-ETHANOL AND BIO-DIESEL FUEL SUPPLY SYSTEMS

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ABSTRACT

Analyses of the yield, energy consumption and GHG emissions for current systems to produce ethanol and bio-diesel are reviewed in the context of European Union (EU-15) application. Energy consumption and net GHG emissions are compared on a per unit fuel and per unit land basis for various systems: corn, sugar cane, wheat, and sugar beet to ethanol; and rapeseed to rape methyl ester (RME). Gross yield of RME is approximately 1 toe ha^{-1}, ethanol from wheat 1.2 toe ha^{-1}, and ethanol from sugar beet 3.4 toe ha^{-1} limiting the quantity of gasoline or diesel fuel use that could be replaced by biofuels using set-aside land available in the EU-15. Energy consumption for crop production and processing to make ethanol or RME in current processes account for about 58-106% of the produced RME or ethanol fuel energy content. Avoided GHG emissions resulting from gasoline or diesel fuel use replaced by biofuels, accounting for fuel system energy use, and crediting GHG offsets for animal feed byproducts, result in 0.4 tC_{eq} ha^{-1} for ethanol from wheat, 1.3 tC_{eq} ha^{-1} for ethanol from sugar beet, 0.6 tC_{eq} ha^{-1} for RME with a wide range of uncertainty stemming from, e.g., uncertainty in agricultural N_2O emissions and byproduct credits. Fluxes of avoided GHG emissions from these biofuel production systems are found to be much less than those from afforestation or reforestation in temperate regions.

REVIEW OF CURRENT BIOFUELS

Biofuel Yields Per Hectare

Systems produce bio-diesel by the extraction of oils from crops (e.g. rapeseed or soybean), transesterifation with, e.g., methanol to make fatty acid esters and glycerol, followed by removal of glycerol [1]. Systems produce fuel ethanol by the extraction of starch or sugar from crops (e.g. corn, sugar cane, sugar beet, or wheat), fermentation to make a dilute ethanol solution, and distillation to make anhydrous ethanol [2]. Yields of biofuels from commercial systems are determined by the yield of sugar, starch or plant oils extracted from harvested crops and the conversion efficiency to ethanol or bio-diesel.

Yields of rapeseed methyl esther (RME) and ethanol are shown in Figure 1. Yield of RME per unit land is lower than ethanol from corn or wheat, which is lower than ethanol from sugar cane or sugar beet. Yields of plant oils are typically lower than yields of sugars and starches [3].

Prospects for improving yields for these biofuel systems by improvements in conversion efficiency are limited; conversion efficiency for ethanol, for example, is approaching the theoretical maximum [3]. Increases in crop yields have been achieved; USA corn yield, for example, has exhibited a 2% annual increase in yield over the last decade, and EU-15 wheat and sugar beet yields each have exhibited a 1% annual increase in yield over the last decade, all with considerable interannual variation [4].

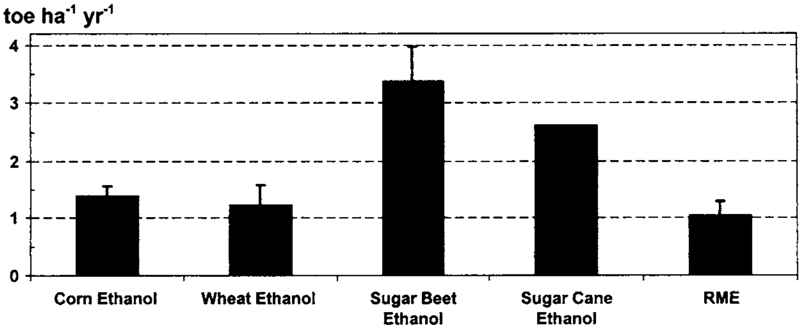

Figure 1: Yield of ethanol and RME per unit cropland given on an energy basis (lower heating value; 1 toe = 42 GJ). Corn ethanol yield is typical for the USA [5]. Wheat and sugar beet ethanol yields are typical for EU-15 [6]. Sugar cane ethanol yield is the average for Brazil in 1995/96 [7]. RME yield is the average for Northern France [6]. Error bars represent the range of yields spanned by studies reviewed by CONCAWE [8].

Net Energy Produced with Biofuels

Increased use of biofuels (ethanol and bio-diesel) is being considered for a variety of reasons including the reduction of GHG emissions. The production of biofuels from plants would lead to no GHG emissions if they did not consume fossil fuels, lead to other GHG emissions such as N_2O emissions from fertilizer use, or lead to loss of plant and soil carbon stocks. It is well known, however, that the production of biofuels requires significant energy to convert chemical components of crops to ethanol or bio-diesel, and to produce and deliver the crop that is consumed in the process.

The energy inputs to produce ethanol or RME can be comparable to the energy contained in the fuels as was found in the studies summarized in Figure 2 and reviewed in detail in other reports [8, 9]. Agriculture energy inputs from fertilizer production, planting and harvesting, crop transport, etc, are lower for sugar cane or sugar beet than for wheat, corn, or rapeseed per unit fuel produced. Energy required for processing is higher for the production of ethanol (e.g. milling, fermentation and distillation) than for RME. In the EU-15, estimated energy inputs range from 58% of energy in RME produced [10, 11] to 106% of energy in wheat-ethanol produced [12]. Some processing energy can potentially be supplied by bioenergy. In the Brazil sugar cane-ethanol system, process energy (see Figure 2) is supplied by ample supplies of bagasse (crushed cane stems) that would otherwise require disposal. For most crops, the supply of agricultural byproducts or residues (e.g. wheat straw) is limited in relation to the energy needs for processing the crops into, for example, ethanol and could, in theory, supply a fraction of the processing energy [8, 9]. Fossil energy consumption avoided by the replacement gasoline or diesel fuels with ethanol or RME is represented by the somewhat lower bar heights for biofuels than for gasoline or diesel in Figure 2. Furthermore, results summarized in Figure 2 do not include energy credits for byproducts such as animal feed or biomass residues. CONCAWE [8] estimates that, in the European context, the percent of fossil fuel energy saved by replacing gasoline with ethanol increases from 17% to 31% of fuel replaced when animal feed credits are included, and fossil fuel energy saved by replacing diesel fuel with RME increases from 47% to 56% of fuel replaced when animal feed credits are included.

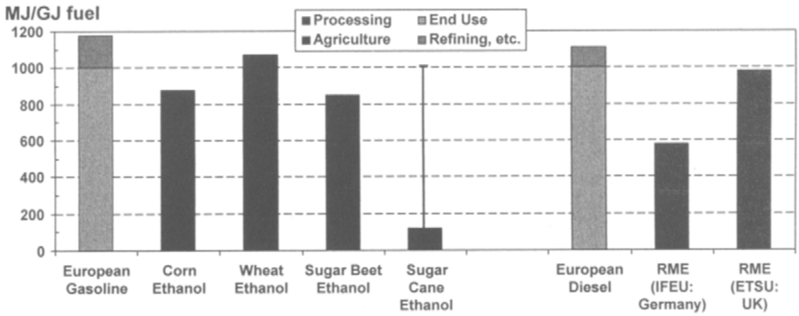

Figure 2: Energy consumed for agriculture (i.e. production of crops) and processing of crops to make biofuels per GJ biofuel produced (lower heating value). Corn-ethanol energy use is typical for good practice in the USA circa 1990 [5]. Wheat-ethanol energy use is estimated for the UK [12]. Sugar beet-ethanol energy use is estimated for France [13]. Sugar cane -ethanol energy use is for Brazil in 1995/96 with the extended bar indicating the additional energy from burning bagasse used to fuel the cane to ethanol process [14]. Two bars for rapeseed to RME energy use are from studies carried out for Germany [10, 11] and the UK [12]. Energy required to produce, refine and deliver gasoline and diesel fuel in Europe is shown [8] along with the energy consumed by end use combustion in vehicles (1 GJ; not shown for biofuels).

Avoided GHG Emissions with Biofuels

GHG emissions incurred producing biofuels subtract from the GHG emissions not emitted by the gasoline or diesel consumption that biofuels might replace. GHG emissions resulting from, and offsets assigned to, byproducts produced along with biofuels further modify net GHG emission estimates. Figure 3 summarizes the net GHG (studies focus on CO_2 and some consider N_2O emissions) emissions avoided per unit cropland for biofuel systems. While the yield of RME per unit land is lower than ethanol from corn or wheat, the energy consumption for ethanol production is higher leading to lower CO_2 emissions avoided for these sources of ethanol than for RME. High sugar yields of sugar cane and beet lead to higher CO_2 emissions avoided per unit cropland. Sugar cane ethanol as produced in Brazil, which makes use of the large quantities of byproduct bagasse (crushed cane stems) as an energy source for the conversion of sugar cane to ethanol, has the highest rate of CO_2 emissions avoided of the biofuels shown in Figure 3.

Fertilizer use for some crops, for example rapeseed, can add not only to CO_2 emissions for fertilizer production, but also, and perhaps more significantly, additional N_2O emissions leading to decreased net GHG avoided from biofuels. While N_2O emission factors remain uncertain, application of IPCC [15] emission factors for N_2O cuts the estimate of CO_2 equivalent emissions avoided by RME shown in Figure 3 by more than a factor of two [8] leading to a fundamental uncertainty in estimates of GHG emission.

Land use required to produce RME at a scale sufficient to avoid a fraction of EU-15 GHG emissions is compared to EU-15 land areas in Figure 4. Given the current area of EU-15 set-aside land of 5.6 Mha [16], CONCAWE [8] calculated that if all set-aside land were to produce a mix of RME and wheat- and sugar beet-ethanol then this would avoid about 0.3% of EU-15's GHG emissions. Available land is clearly a key limitation to large-scale production of biofuels.

Studies of net GHG emissions from biofuel systems usually neglect consideration of changes in plant and soil carbon stocks over harvesting cycles. Soil management practices can add to soil carbon stocks at rates comparable to the rates of emissions avoided shown in Figure 3; of course, such practices could be applied more broadly to agricultural lands [17]. But if biofuel systems lead to deforestation or the establishment of additional cropland, then emissions associated with land use change would far surpass the annual avoided emissions from biofuels; for example, the IPCC [18] lists temperate forest deforestation to cause an emission of about 60 tC ha^{-1}.

Accumulation of carbon stocks is observed in temperate forests. Increases in total carbon stocks -- vegetation and soils -- have been assessed by direct determination of net sources and sinks (i.e. net ecosystem productivity) over periods of 1 or more years; increases in total carbon stocks have been found in temperate forest stands (predominantly mature) to range from 2.5 to 7 tC ha^{-1} yr^{-1} [19]. The IPCC [18] assessed that afforestation and reforestation in temperate regions could be accounted to offset GHG emissions at a rate of 1.5 to 4.5 tC ha^{-1} yr^{-1}. As shown in Figure 3, these rates are larger than estimated emissions avoided by biofuel systems. The common assumption [20] that forest sinks and bioenergy result in similar reductions in net GHG emissions is found to be false for the biofuel systems considered here.

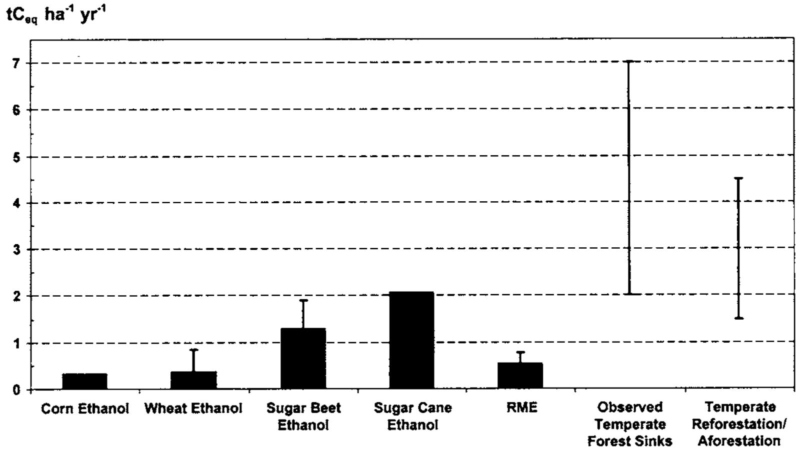

Figure 3: Net GHG emissions avoided by the replacement of gasoline or diesel fuel by ethanol or RME is compared with carbon sinks from temperate forests on a per unit cropland or forestland basis. Emissions avoided shown for the European context (wheat- and sugar beet-ethanol, and RME) are the average and range of studies summarized by CONCAWE [8] including credits for animal feed byproducts but assuming no bioenergy used for processing energy. The CO_2 emissions estimate for the ongoing USA corn-ethanol system includes credits for animal feed byproducts with no bioenergy used for processing energy, while that for the ongoing Brazilian cane-ethanol system accounts for bioenergy use but does not produce animal feed byproducts [3]. For temperate forests, the range of observation-based estimates of CO_2 sinks [19] and the additional sinks that would be expected to be generated by reforestation or afforestation [18] are shown.

Alternative Uses of Biomass

The production of ethanol by the fermentation of cellulose and hemicellulose in biomass (e.g. wood, grass and crop residues) has been proposed as an effective process to avoid GHG emissions [21, 22], although not currently commercial. However, the energy required to make ethanol in this way is greater than the energy of the produced ethanol -- i.e. greater than the energy required for ethanol from any of the systems considered in Figure 2 [8]. The process relies on efficient use of waste biomass (e.g. lignin) to power the system [23]. Of course, biomass could alternatively be used directly for energy (e.g. heat and power) rather than as an energy supply for an energy-inefficient and expensive biofuel system. The cost of producing ethanol from cellulose has yet to match the targets set for this technology [24]. The cost of bio-ethanol in the USA has been estimated to currently be about $1.20 per gallon higher than the cost of gasoline [22]; if this added cost were assigned to avoiding gasoline CO_2 emissions, it would equate to about 440 $ tC^{-1}. CO_2 emissions avoided by the use of ethanol or RME produced in the EU-15 has been assessed to be even more costly [9]. The high cost of biofuels in the EU-15 and the USA relative to gasoline and diesel fuel put biofuels far down the list of options [25] to reduce GHG emissions based on cost effectiveness.

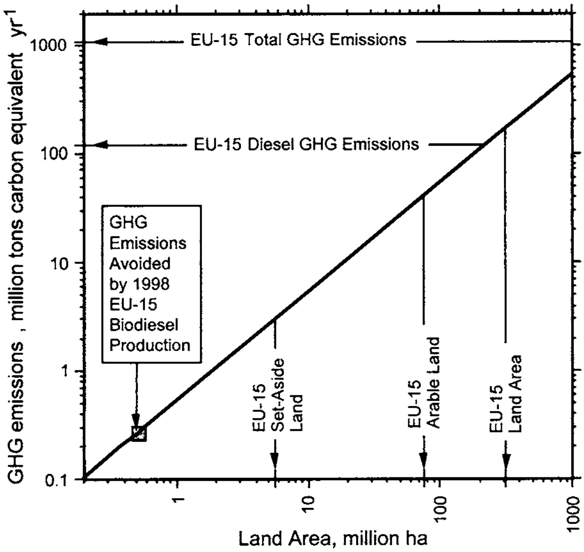

Figure 4: Proportional relationship (diagonal line) between the extent of land required to produce RME and the GHG emissions that would be avoided by using RME as a diesel fuel substitute. GHG avoided per ha for RME follows the value shown in Figure 3 and includes byproduct credits. EU-15 RME production in 1998 [16] at the average yield of Northern France (see Figure 1) is marked by the square symbol. EU-15 land areas and GHG emissions are marked along the axes. Note that the axes are logarithmic.

CONCLUSIONS

Yields of biofuels per unit land area limit their scope as a replacement for gasoline or diesel fuel in the EU-15 context. Analyses show the yield of RME to be less than that of ethanol from wheat or sugar beet. The processing needed for RME, however, is less energy intensive. If fossil energy is used to process biofuels, the rate at which CO_2 emissions may be avoided per unit land becomes higher for RME than for wheat-ethanol, although sugar beet-ethanol remains still higher. Emissions of the GHG N_2O from fertilizer management in crop production adds uncertainty to estimates of GHG emissions avoided as do prospective uses of byproducts. In spite of these uncertainties, emissions avoided with biofuels are significantly lower than observed carbon sinks of temperate forests. The oft-assumed equivalence between rates of forest sinks and emissions avoided with bioenergy does not hold for the biofuels ethanol and RME. Use of bioenergy for heat and power could prove a more effective way to avoid GHG emissions. The costs and prospects of bioenergy systems relative to other alternatives, however, indicate that there is a need for broader portfolios of approaches to address GHG emissions.

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