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Potential land competition between open-pond microalgae production and terrestrial dedicated feedstock supply systems in the U.S.

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ABSTRACT

To date, feedstock resource assessments have evaluated cellulosic and algal feedstocks independently, without consideration of demands for, and resource allocation to, each other. We assess potential land competition between algal and terrestrial feedstocks in the United States, and evaluate a scenario in which 41.5×10^9 L yr^{-1} of second-generation biofuels are produced on pastureland, the most likely land base where both feedstock types may be deployed. Under this scenario, open-pond microalgae production is projected to use 1.2×10^6 ha of private pastureland, while terrestrial biomass feedstocks would use 14.0×10^6 ha of private pastureland. A spatial meta-analysis indicates that potential competition for land under this scenario would be concentrated in 110 counties, containing 1.0 and 1.7×10^6 ha of algal and terrestrial dedicated feedstock production, respectively. A land competition index applied to these 110 counties suggests that 38 to 59 counties could experience competition for upwards of 40% of a county's pastureland, representing 2%–5% of total pastureland in the U.S.; therefore suggesting little overall competition between algae production, terrestrial energy feedstocks and alternative uses for existing agricultural production such as livestock grazing.

1. Introduction

1.1. Background

Second-generation biofuels are expected to be an important contribution to renewable energy options in the U.S. and internationally. Advanced hydrocarbon biofuels, or “drop-in” fuels, and cellulosic ethanol, can displace non-renewable liquid transportation fuels and provide environmental, economic, social, and energy-security benefits [3,35,37]. As one example of exposure to oil price fluctuations, a conflict in the Strait of Hormuz could jeopardize the flow of 2.7×10^9 L (L) day^{-1} of oil, about 20% of the world's oil supply [38].

To improve domestic energy security, the U.S. Energy Independence and Security Act of 2007 (EISA), has set the goal of producing and using 136×10^9 L (36×10^9 gallons) of renewable fuels by 2022 [34]. This ramp-up of biofuels use includes second-generation cellulosic biofuels and bio-based diesel, gasoline, and jet fuel. Further, demand for biopower (i.e. electricity generation from biomass) will likely cause additional demand for biomass feedstocks [18].

Second-generation biofuels can be produced from a wide range of resources, including terrestrial feedstocks (e.g., agricultural residues, forest residues, and herbaceous or woody energy crops, and oil-seed crops) and aquaculture feedstocks (e.g., microalgae, cyanobacteria, and macroalgae). In general, terrestrial feedstocks are widely available, with proven agriculture-based production and logistics systems poised to generate additional feedstocks under the proper economic conditions and/or beneficial use as a rotation crop. Globally, algae-based cultivation makes up the third largest aquaculture crop producing 19×10^6 dry Mg of biomass at an annual value of US$ 5.7 billion; currently and historically, algae have a variety of end uses including human food consumption, nutraceuticals, dry feed for livestock and poultry, and live feed for

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fish and shellfish aquaculture [12,45]. Its use as a renewable energy resource had a significant research effort starting in the late 1970's [31,32,34]. In contrast to terrestrial agriculture and infrastructure, commercial-scale algal feedstock production systems are emerging and not as widely demonstrated, though advantages of algae-derived biofuels include higher yields per unit area per unit time [4,20], production of a variety of fuel end products (e.g., methane, hydrogen, ethanol, biobutanol, renewable diesel, gasoline and jet fuel), and the potential to use large-scale, non-competing water sources such as brackish to saline/hyper-saline groundwater, or seawater [22,25,40].

Site-specific conditions such as climate, current land use, water type, availability and quality, and compatibilities and synergies with extant industries and land-use practices are likely to determine which feedstock type is best suited for any particular application and region. For example, areas with little rainfall, poor soil conditions, and economic proximity to alternative water sources and infrastructure resources may be ideal for algae production, while high-yielding agricultural or forested regions with widely available biomass residues or available land may be best suited for production of terrestrial biomass feedstocks [41]. Research suggests that the land type likely to be converted to both terrestrial dedicated feedstocks and microalgae production is non-irrigated private (non-Federal) pastureland east of the 100th meridian (based on [37,44]. Thus, there is a need to evaluate the potential competing demand between terrestrial and algal feedstocks for pastureland.

1.2. *Related feedstock assessments*

Current research and development of renewable fuels aims to produce advanced biofuels that are cost-competitive with conventional fossil fuels. Part of this research includes evaluating the current and potential future availability and geographic distribution of biomass feedstocks, which must be known, or at least estimated, if strategies for meeting second-generation biofuels production targets are to be developed. Various studies have evaluated national feedstock supply in the U.S. In particular, the U.S. Department of Energy's Bioenergy Technology Office (DOE-BETO) has funded national feedstock assessments. The “Billion-Ton Study” by Perlack et al. [27], was an estimate of potential biomass supplies within the contiguous U.S. based on both available data of current resources and projections of future yield improvements. In support of goals set by the Biomass R&D Technical Advisory Committee [36], this study concluded that there are sufficient U.S. agriculture and forest resources to sustainably provide a billion dry tons of biomass annually, enough to displace approximately 30% of the country's petroleum consumption, thus meeting the Energy Policy Act of 1992 [33]. While this study was a seminal work on evaluating potential supplies, it did not analyze what prices might be needed to incentivize production of this supply or specify from where the resources would come.

Expanding on Perlack et al. [27], the U.S. Department of Energy produced the “Billion-Ton Update” [37]. To assess feedstock quantities available by price, this study employs the Policy Analysis System (POLYSYS), a national economic linear programming model used to determine optimal allocation of private agricultural lands, described in more detail in section 2.1 and De la Torre Ugarte and Ray [10]. Feedstock availability is a function of price, yield scenario, year, crop development status, and other factors. This report suggests that a farmgate price of \$66 dry Mg^{-1} [\$60 dry ton (dt)$^{-1}$] would induce production of between 664 and 1186 dry Mg (732 and 1307 dt) of additional feedstocks, dedicated crops, and forest resources in 2030. Langholtz et al. [18] expanded on these results, identifying farmgate prices needed to procure enough feedstock to meet the combined demand of EISA and projected increases in biopower, calculated at 295×10^6 dry Mg (325×10^6 dt) yr^{-1} in 2022. A farmgate price of \$58.42 Mg^{-1} (\$53.00 dt^{-1}) is needed between 2012 and 2022 to procure this supply, or alternatively, farmgate prices increasing from \$33.00 Mg^{-1} (\$30.00 dt^{-1}) in 2012 to \$68.34 Mg^{-1} (\$62.00 dt^{-1}) in 2022 are needed to procure the same supply, under baseline yield assumptions.

Similar to the U.S. Department of Energy [37] but excluding forest resources, Khanna et al. [17] evaluate the economic availability of biomass feedstocks under six scenarios that capture production of crop residues and herbaceous dedicated biomass crops. This analysis is done using the Biofuel and Environmental Policy Analysis Model (BEPAM), a dynamic, multimarket equilibrium, nonlinear mathematical program that determines land allocation, crop production, and prices in markets for fuel, biofuel, food/feed crops, and livestock in the U.S. They conclude that $617–923 \times 10^6$ Mg of biomass can be produced in 2030 at a farmgate price of \$140 Mg^{-1} depending on yields, cost of production, and land availability.

None of the aforementioned terrestrial feedstock assessments included microalgae as a feedstock. Wigmosta et al. [44] conducted a high-spatiotemporal-resolution national assessment of resource use and production potential for algal biofuels produced at potential open-pond facilities. This study suggests that under current technology, microalgae have the ceiling potential to generate 220×10^9 L (58 BG (BG = billion gallons)) yr^{-1} of renewable diesel, equivalent to 48% of 2010 U.S. petroleum imports for transportation using approximately 5.5% of land area in the conterminous U.S. This particular estimate assumes a fairly conservative growth rate and lipid content of algal feedstocks; however, it is not bound to water resource, nutrient, or economic constraints. By selecting the highest production and least water consuming sites in the country, the study states 17% of 2011 U.S. petroleum imports for transportation fuels[1] can be met using 28×10^{13} L/yr^{-1} (7397 BG yr^{-1}) of freshwater, or 25% of what is currently used for irrigated agriculture. Quinn et al. [28] modeled U.S. productivity based on an industrial-scale outdoor photobioreactor system and estimated a total potential of 1.19×10^{12} (315 BG yr^{-1}) lipid production on 75×10^6 ha of land (including Hawaii). A resource assessment, techno-economic analysis (TEA), and life-cycle analysis (LCA) model harmonization and baseline analysis study [1] provides a quantitative tradeoff of economic, social, and environmental aspects around the production of algal-based renewable diesel using the best-available and publicly available data and knowledge. The study sub-selected 446 4850 ha unit farms (from the original Wigmosta et al. [44] study) located around the coastal areas of the Gulf of Mexico that were able to cumulatively produce renewable diesel at a long-term mean annual rate of 1.89×10^{10} L (5 BG yr^{-1}) and were resource constrained by using a 5% fraction of available freshwater. This baseline scenario estimates costs of \$4.92 L^{-1} (\$18.63 gal^{-1}) of renewable diesel, with significant up-front capital costs making up 70% of the selling price and 60% of capital expenses being attributed to pond construction and pond liners. It should be noted that there are many different system configurations and downstream processing pathways that affect the total costs, for example, a pond without a liner will largely reduce the per-gallon cost, though environmental risks increase (i.e., groundwater contamination through nutrient loading and/or brackish or saline waters into shallow groundwater supplies) and needs to be considered in pond design. As a novel feedstock production system, costs of production and, thus, economic viability of algal feedstocks remain an area of active research (for economic feasibility analysis,

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[1] US petroleum imports were 668×10^9 L yr^{-1} in 2011 (http://www.eia.gov, accessed Sept 26th 2012).