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 $41.5 \times 10^9 \text{ L yr}^{-1}$ 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.

Keywords: Agricultural policy analysis; bioenergy; biofuels, microalgae; land use

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 (Biomass Research and Development Board, 2008; U.S. Department of Energy, 2012; U.S. Department of Energy, 2011). 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 liters (L) day⁻¹ of oil, about 20% of the world’s oil supply (U.S. Energy Information Agency, 2012).

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 liters (36×10^9 gallons) of renewable fuels by 2022 (U.S. Department of Energy, 2010). 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 (Langholtz et al., 2012).

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 fish and shellfish aquaculture (Food and Agricultural Organization of the United Nations, 2012; Wikfors & Ohno, 2001). Its use as a renewable energy resource had a significant research effort starting in the late 1970’s (Sheehan et al., 1998; Spolaore et al., 2006; U.S. Department of Energy, 2010). 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 (Chisti, 2007; Mata et al., 2010), 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 (Murphy & Allen, 2011; Pate et al., 2011; Venteris et al., 2012a).

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 (Venteris et al., 2014a). 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 U.S. Department of Energy, 2011; Wigmosta et al., 2011). 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. (Perlack et al., 2005), 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 (U.S. Department of Energy, 2003), 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 (U.S. Department of Energy, 2007). 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. (Perlack et al., 2005), the U.S. Department of Energy produced the "Billion-Ton Update" (U.S. Department of Energy, 2011). 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 (De la Torre Ugarte & Ray, 2000). 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 1,186 dry Mg (732 and 1,307 dt) of additional feedstocks, dedicated crops, and forest resources in 2030. Langholtz et al. (Langholtz et al., 2012) 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 x 10⁶ dry Mg (325 x 10⁶ 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 (U.S. Department of Energy, 2011) but excluding forest resources, Khanna et al. (Khanna et al., 2011) 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 x 10⁶

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. (Wigmosta et al., 2011) 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 fuels¹ can be met using 28×10^{13} L/yr⁻¹ (7,397 BG yr⁻¹) of freshwater, or 25% of what is currently used for irrigated agriculture. Quinn et al. (Quinn et al., 2012) 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 (ANL/NREL/PNNL, 2012) 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 4,850 ha unit farms (from the original Wigmosta et al. (Wigmosta et al., 2011) 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

¹ US petroleum imports were 668×10^9 L yr⁻¹ in 2011 (<http://www.eia.gov>, accessed Sept 26th 2012).

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, see Beal et al., 2015; Huntley et al., 2015; Richardson et al., 2012).

1.3. Research need: integrated terrestrial/algal assessment and objectives

To date, feedstock resource assessments have evaluated cellulosic and algal feedstocks independently, without consideration of demands for, and resource allocation to, each other. However, both terrestrial and algal biomass feedstocks are likely to be deployed to meet EISA targets and produce second-generation biofuels. Further, it is not known to what extent terrestrial and algal feedstock production systems may compete for the same land resources. Terrestrial and algal feedstock strategies, both assuming land availability, may be double-counting land resources as potentially available, or at a minimum, there may be inadequate accounting of competing demand for certain land resources. Thus, there is a need for an integrated resource assessment that accounts for the combined potential of these two feedstocks. Considering site-specific factors favoring one feedstock type over another, this research would also identify geographical regions with minimal competition, where emphasis could be put on one feedstock type over another. These research aims would be of particular interest to government agencies that fund research and development programs in both terrestrial- and algal-based biofuels programs, such as DOE-BETO.

Widespread land-use competition due to production of both algal and terrestrial feedstocks is not expected, but still is evaluated here as a first step towards integrating algae and terrestrial feedstock resource assessments. One widely-cited benefit of producing biofuels from microalgae is the expectation to not compete with food production. However, the meta-analysis presented here does identify one potential source of land-use competition with terrestrial biomass on pastureland. While this is not expected to be the most immediate obstacle to deployment of algal and terrestrial feedstock production systems, still this research

aims to proactively address concerns of land competition as one element of long-term strategic biofuels planning.

The competitive advantage of algal vs. terrestrial systems will be driven by a mix of fuel-specific (i.e., jet fuel, diesel) and co-product (i.e., livestock and aquaculture animal feed, nutraceuticals) markets, economics, public policy, regulation, resource availability, waste resource capture and utilization and other factors. For example, the cost of production of algae on a per-ton basis is expected to be higher than that of terrestrial feedstocks, yet research and development in algal biofuels persists. This investment continues for many reasons including: 1) algae production may provide unique system-specific environmental benefits (e.g., utilization of waste water, nutrients, heat, and/or CO₂) that terrestrial systems cannot; 2) high-density production footprint and potential for year-round production; 3) active evolution of production system designs to drive capital and operational costs down; 4) niche fuel markets such as aviation fuels; 5) potential for public perception to drive policies that favor some algal biofuels over terrestrial biofuels; and 6) high-value algal co-products may disproportionately contribute to the profitability of algae production systems driving towards a competitive industry. A current example is the U.S. Environmental Protection Agency's Clean Power Plan, including support for carbon capture and utilization, which may increase market opportunities for algae production. Thus, while analysis of the competitive advantage of these two production systems is needed, it is beyond the scope of this analysis.

With this research, we aim to present an integrated biomass resource assessment that: 1) includes both algal and terrestrial feedstocks; 2) accounts for and quantifies the potential competition for land between terrestrial and algal feedstock production; and 3) identifies areas where algal and cellulosic feedstocks have opportunities for production with a minimum of competition for land. This is achieved through a spatial meta-analysis of results from USDOE (U.S. Department of Energy, 2011), Wigmosta et al. (2011), and ANL/NREL/PNNL (2012). In section 2, we present the models, including the terrestrial feedstock land use model, the algal feedstock model, and provide the basis for the land competition model. Section 3 details the methods used to extract pasture lands and presents the pastureland competition index and associated assumptions and applications. Section 4 presents the results of the pastureland

competition index considering two different sources of pastureland data, and sections 5 and 6 provide the discussion and conclusion, respectively.

2. Models

This meta-analysis combines modeling results of projected feedstock production and land use of terrestrial and algal feedstocks, and projected land requirements associated with each. Terrestrial supplies and land use are based on results from USDOE (U.S. Department of Energy, 2011), which are derived from the agricultural-economic model POLYSYS. Algal supplies and associated land use are derived from the open-pond temperature/microalgae growth model and spatial suitability analysis developed by Wigmosta et al. (2011) and further expanded in ANL/NREL/PNNL (2012). The following are descriptions of both models, assumptions used, and implications for this analysis.

2.1. Terrestrial Feedstock Land-use Model: POLYSYS

POLYSYS is used to simulate potential economic policies and agronomic strategies, and to estimate the resulting impacts on the U.S. agricultural sector (De la Torre Ugarte & Ray, 2000; Langholtz et al., 2012; Lin et al., 2000; Ray et al., 1998). POLYSYS is comprised of interdependent modules simulating crop supply for the continental U.S., national crop demands and prices, livestock supply and demand, and agricultural income. Variables that drive the modules include planted and harvested area, production inputs, yield, exports, costs of production, demand by use, commodity price, government program outlays, and net realized income. Conventional crops currently considered in POLYSYS include corn, grain sorghum, oats, barley, wheat, soybeans, cotton, rice, and hay. POLYSYS also considers terrestrial biomass crops for bioenergy. These crops include annual and perennial herbaceous energy crops and coppice and non-coppice woody crops for bioenergy, and the collection of crop and woody residues as additional cellulosic feedstocks. The taxonomy of these modeled feedstocks is described in USDOE (U.S. Department of Energy, 2011).

Biomass feedstocks are projected to be produced on agricultural land based on relative profitability to conventional major crops. POLYSYS can be used to estimate feedstock

237 availability in two ways. Either a specific biomass price or a specific biofuel demand level can
238 be exogenously introduced to the model. If biomass price is exogenously introduced, all
239 feedstocks in all regions are offered the same price per dry Mg, land is allocated to the most
240 profitable regional feedstocks, and the model determines the national supply level associated
241 with the exogenous price. If an exogenous demand for biofuels is introduced, then the model
242 iterates by incrementally increasing the biomass price until the national demand level is
243 reached. By introducing an exogenous demand level, the model determines the equilibrium
244 feedstock price that is necessary to meet this demand. Major modeling assumptions used in
245 POLYSYS are presented in Table 1. More information about POLYSYS assumptions and
246 operations are available from De la Torre Ugarte and Ray (2000). Further documentation
247 regarding the application of POLYSYS to biomass crops is available in the Langholtz et al. (2012)
248 and the appendix of English et al. (2010).

249 Table 1. Major assumptions included in quantification of the potential production of terrestrial
 250 biomass feedstocks using the Policy Analysis System (POLYSYS) agronomic model.

Scope	Assumptions
Agricultural and pasture land base	2007 Census of Agriculture
Agricultural demand	2010 USDA Baseline assumed, extrapolated from 2020 to 2030
Energy crop types	Perennial herbaceous, annual herbaceous, coppice SRWC, non-coppice SRWC
Energy crop yields	Regionally assigned yields based on literature
Pasture intensification	One acre of management-intensive grazing assumed capable of replacing forage production displaced by one acre of pasture converted to energy crops
Energy crop yield improvements	Base-case (1%) and high-yield (2, 3, and 4%)
Farmgate prices	Flat nominal prices
Operational constraints	All crop residues available after sustainability retention coefficients are met are assumed operationally available
Geographic range of energy crops on pastureland	Private, non-irrigated pasturelands east of the 100th meridian
Nutrient replacement costs	Costs of nutrients for 1 dry ton/acre of energy crops included
Adjustments to USDA baseline	Calculations made on harvest rather than production
SRWC plantings	Averaged plantings over rotation cycle
Grower payment	\$10/dry ton additional grower payment reported to be included

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The crop supply module allocates cropland and pastureland at the county level to crop alternatives. Dedicated biomass crops are potentially allocated to pastureland in POLYSYS. Pastureland is the only land type allocated to both algae by Wigmosta et al. (Wigmosta et al., 2011) and terrestrial feedstocks by USDOE (U.S. Department of Energy, 2011), and thus is the only land type evaluated here as potentially being allocated both production systems, resulting in land competition. For estimates of available pastureland in farms, the 2007 Census of Agriculture was queried against certain exclusion criteria related to best management practices of energy crop establishment and sustainability considerations. In the 2007 Census, 169×10^6 ha (417×10^6 acres) are classified as non-wooded pastureland (using the specific classifications “Pastureland” and “Cropland used as Pasture”). It is assumed that pastureland capable of transitioning to dedicated terrestrial biomass production is restricted within POLYSYS to counties that lie east of the 100th meridian that are neither irrigated nor wooded (for documentation on the 100th meridian exclusion criteria, see Coman (1911). This exclusion is the result of insufficient evidence that terrestrial feedstocks can be successfully established on pastureland without supplemental or permanent irrigation. Since the irrigated portion of cropland or cropland pasture is reported as a separate category “irrigated pasture”, we identify non-irrigated pasture by assuming irrigation occurs at equal rates across both pasture and cropland pasture at the county level.

Irrigated pasture acreage exceeding combined non-irrigated pastureland and cropland pasture occurs in 48 counties, with all but nine of those counties located west of the 100th meridian. This amount of irrigated acreage exceeding permanent pasture and cropland pasture is significant, totaling 1.25×10^6 ha (3.10×10^6 acres) with 99.45% occurring in counties on or west of the 100th meridian. To deal with these anomalies, it is assumed that zero acreage is available for terrestrial feedstock production from counties where irrigated pastureland exceeds combined permanent pasture and cropland pasture acreage. Further, the Census of Agriculture includes only private lands. Thus, federal lands are excluded from analysis in POLYSYS.

The amount of pastureland in the 2007 Census of Agriculture occurring in counties that lie east of the 100th meridian is 59×10^6 ha (146×10^6 acres). Using the methodology described above, we exclude: 1) irrigated pastureland; 2) cropland pasture; and 3) counties where the occurrence of irrigated pastureland exceeds combined reported permanent pasture and cropland pasture, this acreage is discounted to 53.41×10^6 ha (132×10^6 acres). In comparison with the national amount of reported pastureland and cropland pasture in farms, our methodology excludes roughly 68% of total US land classified in the USDA Census as “permanent pasture” or “cropland pasture” in farms. Further, as pasture is claimed by dedicated energy crop production livestock forage from grazing can be displaced. To maintain forage and livestock production, POLYSYS includes an assumption requiring that one hectare of pastureland be converted to management intensive grazing for every hectare of pasture converted to dedicated biomass production. As a result, the costs of establishment on pastureland are higher than for cropland due to the costs to intensify grazing (through fencing, fertilizer applications, rotation of cattle, etc.). These four conditions (non-wooded, non-irrigated, non-arid, and forage intensification) lower the total pastureland amount feasibly available for conversion to 26.5×10^6 ha (65.5×10^6 acres), or about 16% of total U.S. pastureland and cropland used as pasture. The biophysical and economic constraints in POLYSYS act together to reduce projected competition of pastureland among terrestrial and livestock systems as intended for the purpose of assessment within the Billion-Ton Update (U.S. Department of Energy, 2011), as well as algal feedstocks, as the focus of this study. More information on POLYSYS, its application, and visualization of the county-level terrestrial biomass resource projections used in this analysis are available at www.bioenergykdf.net.

2.2. Algal Feedstock Modeling

Biomass productivities, associated lipids, resource requirements, and resource supplies are being modeled for microalgae cultured in open ponds in a spatial and biophysical modeling suite referred to as the Biomass Assessment Tool (BAT) (Coleman et al., 2014; Venteris et al., 2012b; Venteris et al., 2014b; Wigmosta et al., 2011). While the BAT is comprised of many modules, the relevant components of the modeling suite used in this study include: 1) a spatial

land suitability model; 2) an open-pond temperature model; and 3) a biophysical microalgae growth model. The land suitability model is a customizable GIS-based multi-criteria analysis tool that defines the location, size, and overall quantity of land that is potentially available for open-pond production within a given geographic domain. As currently configured, the analysis objective identifies potentially non-competitive lands, in terms of social, environmental, food production, and existing/allocated land use. The model uses high-resolution spatial data (900 m²) within the conterminous U.S. and factors in data elements such as slope, and land-use limitations with high- to medium-density developed lands, environmentally sensitive areas, waterbodies, non-eligible cultivated cropland and orchards, and state and federally protected areas, while considering a minimum contiguous area for each potential site of at least 485 ha, thus avoiding significant fragmentation. There are, of course, many additional site-scale factors that must be considered on a site-by-site basis (see for example Venteris et al., 2014a); however, this type of analysis is an appropriate starting point for national-scale analyses. For this study, the results of the land suitability model are aggregated to the county scale to align with the POLYSYS framework. Once the potential algal production sites are identified, hourly meteorological forcing data (Meyer et al., 2008; Nicks & Lane, 1989; Nicks et al., 1993) are assigned and used to run an open-pond temperature and microalgae growth model, resulting in estimates of cumulative biomass production potential over a given unit of time.

Microalgae growth and survival are highly dependent upon light (photosynthetically active radiation - PAR) and water temperature. Different algal strains respond differently to minimum and maximum water temperature ranges as well as a defined optimal temperature range, where maximum biomass accumulation is known to occur, provided the light requirement is satisfied. To address water temperature conditions over time and space, a full mass and energy-balance open-pond temperature model derived from the two-dimensional MASS2 hydrodynamics model (Perkins & Richmond, 2007) was used. The open-pond temperature model uses meteorological variables such as air temperature, net incoming shortwave solar radiation, net atmospheric longwave solar radiation, wind speed, and dew point temperature to calculate heat exchange at the water surface. This results in a depth-averaged pond water temperature and evaporative water loss estimate at an hourly time-step

(Perkins & Richmond, 2007; Wigmosta et al., 2011). The pond model temperatures are used as a key input parameter to a microalgae growth model discussed below. The open-pond temperature model does not consider any supplemental heating of the pond and water temperature is calculated through natural surface energy exchange. For this study, the algal production ponds were established as 30-cm deep raceway ponds with a dimension of 900x45m. A total of 100 ponds are configured within a unit farm, where the remaining area is designated for supporting production infrastructure (i.e., roads, paths, buildings, storage, processing). Major modeling assumptions used in the BAT land suitability model are presented in Table 2

Table 2. Major assumptions included in quantification of land suitability and microalgae pond model using the Biomass Assessment Tool (BAT).

Scope	Assumptions
Pasture Lands	Private, non-irrigated pastureland identified using 2010 Cropland Data Layer (CDL) and 2006 National Land Cover Database (NLCD) on $\leq 1\%$ slope with 485ha minimum area; aggregated to the county-scale
Growth Ponds	Open-pond raceways configured in a 485ha contiguous area with 100 ponds at dimensions of 900x45m with a 30cm water depth; pond temperature modeled with a mass and energy balance hydrodynamics model (MASS2).
Meteorology	Pond and microalgae growth model driven by CLIGEN stochastic meteorology at an hourly time-step for 30-years

The photosynthetic conversion of light into chemical energy in the form of lipids, proteins, and carbohydrates is modeled using a biophysical microalgae growth model detailed in Wigmosta et al. (2011) and ANL/NREL/PNNL (2012). The microalgae growth model

represents the conversion of solar energy to biomass (P_{mass} , per unit area per unit time) and is expressed by:

$$P_{mass} = (\tau_p C_{PAR} E_s) \left[\frac{E_c \varepsilon_b}{E_a Q_r E_p} \right] (\varepsilon_s \varepsilon_t) \quad \text{Equation 1}$$

where τ_p is the transmission efficiency of the incident solar radiation, C_{PAR} is the fraction of PAR from the full solar spectrum, E_s is the energy of the full solar spectrum received at the ground surface (MJ/m^2), E_c is the carbohydrate energy content (MJ mol^{-1}) and contributes in the photosynthetic light to chemical energy conversion, ε_b is the biomass accumulation efficiency, E_a is the energy content of the biomass (MJ/kg^{-1}), Q_r is the required number of photons to free 1 mol of O_2 (mol mol^{-1}) and contributes in representing the photosynthetic process, E_p is the photon energy ($\text{MJ}/\text{mol}^{-1}$), ε_s represents light utilization efficiency, as represented by the Bush Equation (Huesemann et al., 2009), where strain-specific sub-optimal light conditions (inhibited or light saturation exceedance) reduces photon absorption and thus reduced biomass conversion, and finally, ε_t is strain-specific growth efficiency as a result of water temperature-based growth curves established by min/max and optimal water temperature ranges.

For this study, we assume only the lipid fraction of the biomass is used in the production of a renewable diesel end product as opposed to a whole biomass conversion technology such as hydrothermal liquefaction (HTL). This approach is consistent with the USDOE Harmonization study (ANL/NREL/PNNL, 2012). The lipid extraction pathway allows for remaining biomass to be used as a co-product and/or used in an anaerobic digestion process for methane generation (i.e., electricity production) and nutrient recycling.

The conversion of the biomass lipid fractions to produce a resulting volume of renewable diesel normally include efficiency multipliers such as extraction efficiency and fuel upgrading efficiency. To allow for similar comparison to terrestrial energy crops, these

efficiencies are not included, thereby the biomass to renewable diesel, RD , (L/ha^{-1}) conversion is represented by:

$$RD = \left[\left(\frac{B(H_e * f_{oil})}{TAG_d} \right) \right] \quad \text{Equation 2}$$

where B is AFDW biomass in kg/ha^{-1} , H_e is the harvest efficiency, f_{oil} is the lipid fraction of the biomass, and TAG_d is the density of triacylglycerol (TAG) lipid in units of kg/L^{-1} . We assume here that the entire lipid fraction is TAG. The microalgae growth model outputs total biomass as an ash-free dry weight (combined carbohydrates, proteins, and lipids), lipids in volume, and water use by a series of time windows including daily, monthly, seasonal, and annual. Microalgae growth model parameters used in this study are listed in Table 3.

Table 3. Parameters used in the microalgae growth model.

Parameter	Value
τ_p	0.90
C_{PAR}	0.458
E_s	Input from hourly meteorology (MJ/m^2)
E_c	$0.4825 MJ mol^{-1}$
ε_b	0.80
E_a	$21.7 MJ/kg^{-1}$
Q_r	$8 mol mol^{-1}$
E_p	$0.2253 MJ/mol^{-1}$
ε_s	Photosynthetic Light Saturation: $150 \mu mole m^2 s^{-1}$ Incident Light Intensity: Input from hourly meteorology ($\mu mole m^2$)
ε_t	Min: $10.0^\circ C$ Max: $35^\circ C$ Optimal Range: $20.0-30.0^\circ C$
B	(kg/ha^{-1})
H_e	0.95
f_{oil}	0.25
TAG_d	$0.909 kg/L^{-1}$

Large-scale production of biomass, whether for food or energy, typically requires significant quantities of energy and water in “upstream” processes associated with the

production and transportation of fertilizers. In the case of microalgae, CO₂ is an additional nutrient not required for terrestrial crops and can add additional logistical, resource, and facility siting burden; however, co-location with point-source CO₂ emitters, such as ethanol production or coal-fired power plants, can make beneficial use of a waste product and potentially reduce CO₂ supply costs. Industrial waste heat can provide a means for maintaining optimal pond temperature in colder climates, used for heat exchange to anaerobic digestion, or other beneficial use. Depending on the downstream process, microalgae have an advantage over other energy crops in that nutrient recycling can be put in place through anaerobic digestion of the biomass once the lipids have been extracted, thus producing a high-density nutrient mix that can be returned to the ponds; the digestion process also produces bio gas that can be used to offset imported electricity at the site (ANL/NREL/PNNL, 2012). In addition, pond systems can implement water recycling systems to reduce the total water use and limit the amount of concentrate that needs to be treated and disposed. These system designs can reduce upstream lifecycle resource demands and energy costs associated with their production and transport; however site-scale evaluations need to ensure avoidance of net energy losses (ANL/NREL/PNNL, 2012; Clarens et al., 2010; U.S. Department of Energy, 2010).

2.3. Summary of terrestrial and algal land competition modeling

Results from USDOE (U.S. Department of Energy, 2011) and Wigmosta et al. (Wigmosta et al., 2011) provide spatially-explicit allocation of terrestrial and algal feedstock production (summarized in Figure 1). Three assumptions used in the terrestrial and algal modeling narrow the focus on counties where there may be competition for land between these two potential feedstocks. In the algae spatial suitability analysis, algae production is assumed undesirable on agricultural lands, due to inflexibility in transitioning land between food and fuel production systems. In the modeling of terrestrial feedstocks in POLYSYS, pastureland west of the 100th meridian was excluded from consideration for conversion to terrestrial feedstocks, as is irrigated pastureland east of the 100th meridian, for reasons described in Section 2.1. Thus, this analysis is focused on the 110 counties that could potentially produce either terrestrial or algal feedstocks on pastureland.

Figure 1. Private pasture allocation to terrestrial and algal production by state. (In some states potential production on pastureland is not visible in this graphic).

Methods differ between the spatial suitability analysis for algae and the projections of allocation of land for terrestrial feedstock production in POLYSYS. The former is based on current physical landscape, land use, and social constraints, while the latter additionally allocates land based on system profitability vis-à-vis alternative land uses. However, these potential land use projections provide the best available data at the time of this writing, and are used as a starting point for comparative analysis of land use allocation between these two broad feedstock categories. This is intended to be the first in a series of studies to identify the best and most probable feedstock allocation scenarios.

3. Methods

Based on the meta-analysis of results from USDOE (U.S. Department of Energy, 2011) and Wigmosta et al. (Wigmosta et al., 2011), the only type of land that is potentially accessible for both terrestrial dedicated feedstocks and microalgae production is non-irrigated private (non-Federal) pasture land east of the 100th meridian. Using the land suitability model developed under Wigmosta et al. (Wigmosta et al., 2011), the land use / land cover data was updated in this study to include the 2010 Cropland Data Layer (CDL) from the USDA National Agricultural Statistics Service (USDA-NASS) data year 2010) and the 2006 National Land Cover Database (NLCD) (Fry et al., 2011). The CDL is a high-resolution remotely-sensed annual data product produced by the USDA's National Agricultural Statistics Service. Using multi-sensor data fusion, the CDL product focuses on land cover in agricultural areas defined by the Farm Service Agency's Common Land Unit (CLU) boundaries (i.e., delineations of farm fields).

The NLCD is a high-resolution (900 m²), high-quality remotely-sensed land use/land cover data product covering the conterminous U.S. and produced by a consortium of U.S. Federal agencies. To ensure capture of other pasturelands that may fall outside of the formal CLU boundaries, the NLCD 2006 was used to inform land cover strictly outside the CDL 2010 classification areas. Using the updated suitable areas data, additional spatial analysis was conducted using pastureland classified areas from the CDL and NLCD datasets, producing suitable land areas for pasture-only areas. Additionally, Federal land ownership was integrated into the suitable pasturelands to: 1) evaluate the national significance of pastureland on Federally-owned lands; 2) understand the potential for how much suitable pastureland exists on potentially leasable Federal land; and 3) eliminate any suitable pastureland located within Federal lands from the analysis to be consistent with the 2007 Census of Agriculture which only considers private land (see Table 4). The non-Federal suitable pasturelands were aggregated from their nominal scale of 900 m² to a county-scale summary of total available lands in order to conduct analysis with POLYSYS results.

Table 4. National area analysis of pastureland in the conterminous U.S. including Federal land designations, potentially leasable Federal lands, and breakout of suitable pasturelands east and west of the 100th meridian in actual area and percentage of total U.S. pastureland and percentage of suitable pastureland.

Land Description	Area (ha)	% of National Pastureland Total	% of Suitable Total
Total U.S. pastureland	54,351,044	-	-
Total pastureland suitable for microalgae land suitability screening	1,255,441	2.3%	-
Total suitable pastureland under federal ownership	46,320	0.09%	3.7%
Total suitable pastureland under potentially leasable federal lands	43,300	0.08%	3.4%
Total suitable pastureland east of the 100th meridian	170,345	0.31%	13.6%
Total suitable pastureland west of the 100th meridian	1,085,096	2.0%	86.4%

3.1. Pastureland Competition Index

To evaluate potential competition between terrestrial dedicated biomass feedstocks and open-pond microalgae production, we calculate county- and state-level pastureland competition indices (PCI). Notably, pastureland acreage estimates differ between the CDL and those reported from the Census of Agriculture. While both these data sources come from the USDA National Agricultural Statistics Service (NASS), they are based on different methodologies. The CDL is based on remotely-sensed satellite imagery, while results from the Census of Agriculture are based on farm survey responses. An unpublished comparison of these two data sources suggests that some land-use categories have high correlation between these two data sources for the counties used in this analysis, (e.g., Pearson correlation coefficient values of 0.97, 0.97, and 0.95, for soybean (n=253), wheat (n=241), and corn (n=282), respectively) while pastureland (n=410) shows a greater discrepancy between these two data sets (0.67). For comparative purposes, we calculate PCI using two approaches, based on pasture from 1) the CDL/NLCD and 2) derived from the Census of Agriculture, using Equations 3 and 4 below:

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$$PCI_{CDL} = \frac{(A+T)}{P_{CDL}} \quad \text{Equation 3}$$

476

$$PCI_{CA} = \frac{(A+T)}{P_{CA}} \quad \text{Equation 4}$$

477

478 where variables are:

479

PCI_{CDL} =PCI calculated using private pasture from the CDL/NLCD, 2010/2006 in the denominator.

480

481

PCI_{CA} =PCI calculated using private pasture from the USDA 2007 Census of Agriculture in the denominator.

482

483

A=conversion of CDL/NLCD, 2010/2006 private pasture to algae (ha).

484

T=conversion of pasture to terrestrial feedstocks (USDOE (U.S. Department of Energy,

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2011), under the base case scenario, assuming \$66 Mg⁻¹ (\$60 dt⁻¹) farmgate price, with

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results for year 2022 (ha).

487

P_{CDL} =Private pasture from CDL/NLCD pastureland, 2010/2006 (ha).

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P_{CA} =Private pasture in farms (permanent pasture and cropland pasture, USDA 2007 Census of Agriculture) (ha).

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The PCI correlates to pastureland competition such that lower PCI values indicate reduced

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competition for pastureland. A higher PCI value is related to higher potential pastureland use

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competition. The value may reach or exceed one due to the fact that the assumed denominator

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in the index is generated from separate estimation procedures that the authors argue are

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complementary, rather than in conflict, with efforts to quantify potentially available land for

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production.

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Further, to evaluate the proportion of terrestrial and algal pastureland conversions, the

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following additional equations are used:

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$$T_{(CDL)} = \frac{T}{P_{CDL}} \quad \text{Equation 5}$$

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501

$$A_{(CDL)} = \frac{A}{P_{CDL}} \quad \text{Equation 6}$$

$$T_{(CA)} = \frac{T}{P_{CA}} \quad \text{Equation 7}$$

$$A_{(CA)} = \frac{A}{P_{CA}} \quad \text{Equation 8}$$

Where Equation 5 represents the proportion of CDL-derived pasture allocated to terrestrial dedicated feedstocks, Equation 6 represents the proportion of CDL-derived pasture allocated to algae production, Equation 7 represents the proportion of Census-derived pasture allocated to terrestrial dedicated feedstocks, and Equation 8 represents the proportion of Census-derived pasture allocated to algae production. These equations are used to calculate values in Figures 4 and 5. A generalized work flow of the methodology described above is illustrated in Figure 2.

Figure 2. Generalized work-flow diagram to evaluate potential land-use competition between terrestrial and algal feedstocks.

3.2. Scenario assumptions

To evaluate possible land competition under a high-production scenario, this analysis simulates provision of 445×10^6 dry Mg of biomass in 2022, including 58×10^6 dry Mg of algal production on pastureland, and 109×10^6 dry Mg of terrestrial production on pastureland. The remaining 277×10^6 dry Mg of biomass includes terrestrial feedstocks produced on non-pastureland (i.e. crop residues, dedicated terrestrial feedstock production on non-pastureland, and forest biomass) shown available by the same POLYSYS modeling scenario described above in sections 2.1 and 2.3. From a policy perspective, this 445×10^6 dry Mg of biomass in 2022 is over 50% more than the 295×10^6 dry Mg that would be required to meet a combination of 2022 EISA targets and projected increase for biopower (Langholtz et al., 2012). The additional 150×10^6 dry Mg could simulate increased demand for domestic biofuels, or could be allocated to EISA provisions for “biomass-based diesel requirements” which are “to be determined by EPA through a future rulemaking, but no less than 1.0 billion gallons” (U.S. Environmental Protection Agency, 2009) . Further, the algae production simulated here would produce only 12×10^6 L of the estimated 220 L that could potentially be produced in the conterminous U.S. (Wigmosta et al., 2011). In sum, the land competition simulated here represents a production scenario exceeding anticipated demand by 50%, and excluding additional non-pasture locations for algae production.

In light of various uncertainties including future biofuels policies, bioenergy conversion technologies, and volatility in supplies of petroleum and alternatives such as natural gas, this simulation is not intended to be a projection. Rather this scenario is used to evaluate possible land completion in a high-production biofuels scenario, acknowledging that realized production and associated land requirements could be less.

In sum, terrestrial feedstock supplies of 386×10^6 dry Mg in 2022, and associated land use, come from a POLYSYS simulation assuming a farmgate price of $\$66 \text{ dry Mg}^{-1}$, using dedicated feedstocks limited to non-irrigated private land east of the 100th meridian. Algal feedstock supplies and associated land use are based on Wigmosta et al. (Wigmosta et al.,

2011) described in section 2.2 with updates completed for this study in this section above. Assumptions and scenarios of the terrestrial and algal simulations are summarized in Table 5.

Table 5. Summary of assumptions defining conversion of pasture to terrestrial and algal feedstock production systems.

	Open-pond microalgae production	Terrestrial dedicated feedstock supply systems
Study	Wigmosta et al. (2011); ANL/NREL/PNNL (2012)	DOE (2011) (U.S. Department of Energy, 2011), Langholtz (2012)(Langholtz et al., 2012)
Projection year	2022 (subject to climate change impacts)	2022 (subject to climate change impacts)
Land-use data set	Remotely-sensed USDA NASS CDL/NLCD (2010/2006)	USDA NASS Census of Agriculture
Study-specific assumptions	Scenario uses long-term stochastic climatology to drive growth and does not consider potential resource limitations that would inhibit or prevent cultivation.	Base case scenario, farmgate price of \$66 dry Mg ⁻¹ , dedicated feedstocks limited to non-irrigated private land east of the 100 th meridian

3.3. PCI Application

From the assumptions described above, 1,897 US counties are identified as converting 10 x 10⁶ ha of private pastureland to terrestrial dedicated feedstock supply systems, 251 counties convert 0.3 x 10⁶ private pastureland to open-pond microalgae production, and 110 counties are identified as converting some 4.6 x 10⁶ acres of pastureland to both terrestrial dedicated feedstock supply systems (3.7 x 10⁶ ha) and open-pond microalgae production (0.9 x 10⁶ ha). Application of the PCI is focused first on these 110 counties where both potential land uses are present under these simulations, located primarily in the Gulf South and minority of counties in the northern plains, corn belt, and the West South Central states (Figure 3), and in further analysis is also applied to the conterminous U.S. states.

Figure 3. Counties with potential for private pasture allocation to terrestrial dedicated feedstock supply systems (orange), open-pond microalgae production (yellow), or both (green).

4. Results

Equations 3 and 4 were used to calculate PCI_{CDL} and PCI_{CA} , respectively, at the county and state level. In the scenarios used here, 110 counties, contained in eleven states, private pastureland would potentially be exposed to competition for both algal and terrestrial dedicated feedstock production. Of these 110 counties, most have PCIs less than 0.4. For example, 51 and 72 of the 110 counties have PCIs less than 0.4 based on the PCI_{CDL} and PCI_{CA} , respectively (Tables 5 and 6, and Figures 4 and 5). This suggests that the majority of the counties that are likely to produce both algal and terrestrial dedicated feedstocks, as well as the remaining 3,000 of the 3,110 U.S. counties, are unlikely to have significant competition between terrestrial and algal feedstock production for land in general and pastureland

specifically, even producing 12.0×10^9 L and 124.4×10^9 L of algal- and terrestrial-feedstock based biofuels, respectively (including 12.0×10^9 L and 29.5×10^9 L of algal and terrestrial production, respectively, on pastureland). In sum, this would provide 136.4×10^9 L, or 20% of 668.0×10^9 L of petroleum imports in 2011.

Table 6. Count, area, and land-use intensity of 110 counties potentially employing both terrestrial and dedicated feedstock supply systems on pastureland (based on the 2010/2006 CDL/NLCD).

PCI _{CDL} categories ^a	Count (CDL- based) ^b	Area to terrestrial (ha) ^c	Area to algal (ha) ^d	Combined pasture conversion ^e	CDL private pasture ^f	% of private CDL pasture in 110 counties ^g	% of private CDL pasture in U.S. ^h
0-0.19	8	38,261	7,441	45,703	411,883	1%	0.1%
0.2-0.39	43	580,899	71,028	651,926	2,180,012	13%	1.2%
0.4-0.59	24	400,817	133,162	533,979	1,114,367	10%	1.0%
0.6-0.79	14	286,436	225,377	511,813	723,858	10%	1.0%
0.8-1.0	9	139,556	176,098	315,654	364,964	6%	0.6%
>1	12	255,922	355,885	611,807	401,476	12%	1.2%
Total	110	1,701,891	968,991	2,670,882	5,196,561	51%	5.1%

^a PCI_{CDL} categories.

^b Frequency of PCI_{CDL} values calculated with Equation 3.

^c Pastureland area converted to terrestrial dedicated feedstock supply systems under the modeling scenario described in Table 5.

^d Pastureland area converted to algae production under the modeling scenario described in Table 5.

^e Sum of the previous two columns.

^f CDL/NLCD private pasture of counties in PCI_{CDL} range.

^g Combined pasture conversion as a percent of total private pastureland, as quantified in the CDL dataset, in the 110 counties.

^h Combined pasture conversion as a percent of total private pastureland, as quantified in the CDL dataset, in the U.S.

ⁱ Combined pasture conversion as a percent of total private pastureland, as quantified in the 2007 Census of Agriculture, in the 110 counties.

^j Combined pasture conversion as a percent of total private pastureland, as quantified in the 2007 Census of Agriculture, in the U.S.

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605 Table 7. Count, area, and land-use intensity of 110 counties potentially employing both
 606 terrestrial and dedicated feedstock supply systems on pastureland (based on 2007 Census of
 607 Agriculture).

PCI _{CA} categories ^a	Count (Census- based) ^b	Area to terrestrial (ha) ^c	Area to algal (ha) ^d	Combined pasture conversion ^e	Census private pasture ^f	% of Census pasture in 110 counties ^g	% of private CDL pasture in U.S. ^h
0-0.19	7	42,339	6,412	48,751	462,471	1%	0.0%
0.2-0.39	65	1,126,197	140,789	1,266,986	3,942,049	19%	0.8%
0.4-0.59	25	433,554	358,410	791,964	1,563,988	12%	0.5%
0.6-0.79	5	39,146	147,325	186,472	272,481	3%	0.1%
0.8-1.0	3	27,373	105,826	133,200	154,614	2%	0.1%
>1	5	33,281	210,228	243,509	201,955	4%	0.1%
Total	110	1,701,891	968,991	2,670,882	6,597,559	40%	1.6%

608 ^a PCI_{CA} categories.

609 ^b Frequency of PCI_{CA} values calculated with Equation 4.

610 ^c Pastureland area converted to terrestrial dedicated feedstock supply systems under the modeling
 611 scenario described in Table 5.

612 ^d Pastureland area converted to algae production under the modeling scenario described in Table 5.

613 ^e Sum of the previous two columns.

614 ^f 2007 Census of Agriculture private pasture of counties in PCI_{CDL} range.

615 ^g Combined pasture conversion as a percent of total private pastureland, as quantified in the 2007
 616 Census of Agriculture, in the 110 counties.

617 ^h Combined pasture conversion as a percent of total private pastureland, as quantified in the 2007
 618 Census of Agriculture, in the U.S.

620
 621 Figure 4. Frequency distribution of county-level terrestrial pastureland use, algal pastureland
 622 use, and PCI_{CDL} values, derived from Equations 5, 6, and 3, respectively, applied to 110 U.S.
 623 counties likely to convert pastureland to algal and terrestrial dedicated feedstock supply
 624 systems under a high-biofuels production scenario.

625
 626 Figure 5. Frequency distribution of county-level terrestrial pastureland use, algal pastureland
 627 use, and PCI_{CA} values, derived from Equations 7, 8, and 4, respectively, applied 110 U.S.
 628 counties likely to convert pastureland to algal and terrestrial dedicated feedstock supply
 629 systems under a high-biofuels production scenario.

630 Under these assumptions, competition for pastureland between terrestrial and algal
 631 feedstock production could be realized in some areas. For example, 59 and 38 counties have

PCIs greater than 0.39, based on the PCI_{CDL} and PCI_{CA} , respectively. These counties are concentrated primarily in the West South Central states and Florida (Figures 6 and 7). While these potential conflicts are notable, combined terrestrial and algal feedstock production in areas with PCIs greater than 0.39 collectively use only 3.8% and 0.8% of U.S. pastureland reported by the CDL and Census of Agriculture, respectively (derived from Tables 5 and 6).

Summaries at state and national levels elucidate potential pastureland competition within the context of all private pasturelands, including counties without allocation of pastureland to terrestrial or algal dedicated feedstock supply systems (Table 8). For the 48 contiguous states, PCI_{CDL} and PCI_{CA} values range from 0.0-1.23 and 0.0-0.39 respectively. Total combined conversion of pastureland to algae and terrestrial feedstocks under the high-production scenario simulated here uses 29% and 9% of private pastureland reported by the CDL and Census of Agriculture, respectively.

Figure 6. County-level land use competition index based on the CDL/NLCD derived from Equation 3. (Counties with competition between algal and terrestrial production are limited to green areas shown in Figure 3).

Figure 7. County-level land use competition index based on the Census of Agriculture derived from Equation 4. (Counties with competition between algal and terrestrial production are limited to green areas shown in Figure 3).

655 Table 8. Allocation of pasture to algae production and dedicated feedstocks, private pasture
656 values based on the CDL and Census of Agriculture, and pastureland competition indexes
657 (based Equations 3 and 4), by state.

State	Private pasture to algae	Private pasture to terrestrial	Combined pasture to terrestrial and algae	Private Pasture (CDL)	Private Pasture (Census of Agriculture)	PCI _{CDL}	PCI _{CA}
------(hectares)-----							
AL	1,040	337,197	338,237	1,603,556	1,070,021	0.21	0.32
AZ	543	0	543	42,443	5,287,266	0.01	0.00
AR	11,524	421,128	432,653	1,724,804	1,358,118	0.25	0.32
CA	12,736	0	12,736	695,953	5,431,393	0.02	0.00
CO	4,996	0	4,996	574,880	7,502,159	0.01	0.00
CT	0	5,476	5,476	86,039	18,347	0.06	0.30
DE	0	2,001	2,001	49,669	6,319	0.04	0.32
FL	545,450	304,285	849,735	1,315,094	1,476,650	0.65	0.58
GA	0	217,504	217,504	1,201,168	777,404	0.18	0.28
ID	0	0	0	316,210	2,024,650	-	-
IL	0	129,188	129,188	1,246,926	483,738	0.10	0.27
IN	0	88,791	88,791	665,472	333,849	0.13	0.27
IA	0	291,545	291,545	1,861,353	1,110,746	0.16	0.26
KS	6,074	1,062,806	1,068,880	1,907,071	5,933,612	0.56	0.18
KY	0	586,598	586,598	2,237,650	1,774,842	0.26	0.33
LA	30,247	250,523	280,771	669,194	875,222	0.42	0.32
ME	0	12,051	12,051	148,939	40,077	0.08	0.30
MD	0	29,490	29,490	316,066	88,669	0.09	0.33
MA	0	7,220	7,220	104,585	25,764	0.07	0.28
MI	0	90,136	90,136	1,092,128	277,378	0.08	0.32
MN	11,407	240,618	252,025	1,605,708	886,564	0.16	0.28
MS	3,403	318,115	321,518	1,236,030	962,546	0.26	0.33
MO	0	1,132,123	1,132,123	5,239,806	3,529,383	0.22	0.32
MT	11,878	0	11,878	552,152	16,719,146	0.02	0.00
NE	887	271,710	272,596	233,288	4,985,250	1.17	0.05
NV	13,766	0	13,766	162,160	1,765,215	0.08	0.01
NH	0	6,248	6,248	74,678	20,616	0.08	0.30
NJ	0	12,691	12,691	91,600	37,805	0.14	0.34
NM	462	0	462	35,216	13,141,605	0.01	0.00
NY	0	129,056	129,056	1,751,861	402,301	0.07	0.32
NC	0	153,194	153,194	1,285,284	517,530	0.12	0.30
ND	7,621	180,020	187,640	1,450,440	4,465,579	0.13	0.04
OH	0	182,627	182,627	1,140,076	564,801	0.16	0.32
OK	13,405	2,249,248	2,262,653	1,951,067	8,639,095	1.16	0.26
OR	29,064	0	29,064	692,996	3,953,283	0.04	0.01
PA	0	153,630	153,630	1,609,966	456,633	0.10	0.34
RI	0	931	931	9,445	3,134	0.10	0.30

State	Private pasture to algae	Private pasture to terrestrial	Combined pasture to terrestrial and algae	Private Pasture (CDL)	Private Pasture (Census of Agriculture)	PCI _{CDL}	PCI _{CA}
SC	0	111,762	111,762	629,344	356,603	0.18	0.31
SD	78,496	170,445	248,941	1,875,807	9,725,057	0.13	0.03
TN	0	503,075	503,075	1,928,238	1,510,358	0.26	0.33
TX	436,471	3,589,840	4,026,311	5,915,532	35,920,463	0.68	0.11
UT	8,848	0	8,848	491,848	3,531,624	0.02	0.00
VT	0	22,361	22,361	241,490	74,402	0.09	0.30
VA	0	331,221	331,221	1,672,996	1,066,845	0.20	0.31
WA	4,667	0	4,667	327,637	1,976,797	0.01	0.00
WV	0	168,184	168,184	466,160	524,828	0.36	0.32
WI	0	190,016	190,016	1,565,310	587,269	0.12	0.32
WY	7,320	0	7,320	317,149	11,049,418	0.02	0.00
Total	1,240,305	13,953,057	15,193,361	52,412,492	163,270,374	0.29	0.09

5. Discussion

These results suggest that while there is potential for land competition between terrestrial and algal feedstock production, it is likely limited to pastureland areas of about 110 counties primarily in the Gulf South. Further, biomass production on these 110 counties represents only about 25% of the total potential in the national simulation. Potentially competing lands in these 110 counties include 1.7×10^6 ha of terrestrial production and 1.0×10^6 ha of open-pond microalgae production. Combined, these areas could produce approximately 85×10^6 Mg year⁻¹ of the 445×10^6 Mg year⁻¹ of biomass. Excluding production in these 110 counties, total potential production would surpass 370×10^6 Mg from other areas, still greater than the 295×10^6 dry Mg that would be required to meet a combination of 2022 EISA targets and projected increase for biopower. Thus, land competition between terrestrial and algal feedstock production is not expected to compromise biofuels production strategies that include both feedstock types.

Inherent to the analysis of terrestrial feedstock production by USDOE (U.S. Department of Energy, 2011) are modeling constraints requiring that projected future demands for food, feed, and fiber domestic consumption and exports are met before any land is allocated to dedicated biomass feedstock production. To maintain adequate pastureland acres, POLYSYS modeling is constrained to require that for every hectare of pasture converted to dedicated

feedstock production, an additional hectare of pastureland is converted to management intensive grazing (MIG), with associated production budgets and productivity. MIG can help maintain forage production on less pastureland, and can mitigate effects of reduced pastureland availability with the potential to provide economic and environmental benefits (e.g., Conant et al., 2003; Dartt et al., 1999; Gerrish, 2004). Considering that less than 51% of pastureland in the 110 counties with competition is shown to convert to terrestrial and algal feedstock production as expressed by PCI_{CDI} or PCI_{CA} (Tables 4 and 5), the MIG assumption as applied in USDOE (U.S. Department of Energy, 2011) could allow for almost all forage production to be met in these 110 counties producing both terrestrial and algal biofuels.

Because pastureland productivity varies by region, the impact of pastureland conversion to dedicated feedstock supply systems on the livestock industry at the national level cannot be assessed with certainty from these results. However, at this high level of biofuels production yielding 445×10^6 dry Mg of biomass between terrestrial and algal feedstocks, only 9% and 29% of pastureland nationally would be displaced based on PCI_{CDL} and PCI_{CA} , respectively. The MIG assumption described above, if correct, would mitigate this pastureland displacement, even at these levels of production of second-generation biofuels, exceeding current national targets.

6. Conclusions

Future energy demands may drive conversion of pastureland to production of algal and/or terrestrial dedicated feedstocks. A meta-analysis of two national resource assessments suggests that private pastureland east of the 100th meridian is the only likely land base that may be pressured by conversion to both terrestrial and algal bioenergy production systems. Under an aggressive biofuels production scenario yielding 41.5×10^9 L yr⁻¹ of second-generation biofuels, 110 counties converted 1.7×10^6 and 1.0×10^6 pastureland ha to terrestrial and algal dedicated feedstock supply systems, respectively, representing 40% of the pastureland in these 110 counties, and 1.6% of private pastureland in the US as a whole, as reported by the Census of Agriculture in 2007.

In this analysis we demonstrate that, at the national level, independent commercialization efforts that might allocate land to algal and terrestrial feedstocks reveal little conflict with each other, and little conflict with alternative uses for existing agricultural

production (e.g. livestock grazing). From a policy perspective, they represent complimentary sources for bioenergy production and their industries may develop in parallel to increase domestic renewable energy production. Additionally, the comparative advantage of each of these feedstocks is evident in the assessment of the geographic regions in which independent projections have been made. While investors may face competition to finance large-scale projects, the regional advantage of terrestrial feedstocks is likely limited to the eastern half of the country, whereas algal feedstock production may be limited to areas outside key agricultural producing regions and at lower rates of pasture utilization. In sum, this research quantitatively indicates that land competition between terrestrial and algal feedstocks is not a constraint on national biofuels development strategies in the United States.

Pioneer algae production projects are likely to be deployed where economic synergies reduce costs. Thus, current and future research aims to evaluate the economic availability of algal feedstocks associated with potential co-locating strategies, e.g. with power plants for CO₂ utilization. As economics of algae production are refined and elucidated, future research should integrate algae resource assessment in an economic modeling framework, to evaluate economic tradeoffs between the two feedstock types. Future economic analysis can further explore other resource constraints and environmental externalities. We aim to incorporate terrestrial and algal feedstock production and associated land-use change within a common modeling framework. County-level results of this research are available at www.bioenergykdf.net.

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