Final Report

Meeting the Demand for Biofuels: Impact on Land Use and Carbon Mitigation

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Purpose of this Research

The purpose of this research was to develop an integrated, interdisciplinary framework to investigate the implications of large scale production of biofuels for land use, crop production, farm income and greenhouse gases. In particular, we examine the mix of feedstocks that would be viable for biofuel production and the spatial allocation of land required for producing these feedstocks at various gasoline and carbon emission prices as well as biofuel subsidy levels. The implication of interactions between energy policy that seeks energy independence from foreign oil and climate policy that seeks to mitigate greenhouse gas emissions for the optimal mix of biofuels and land use will also be investigated. This project contributes to the ELSI research goals of sustainable biofuel production while balancing competing demands for land and developing policy approaches needed to support biofuel production in a cost-effective and environmentally friendly manner.

The objectives of this research are to (a) determine yield and greenhouse gas mitigation benefits, in the form of soil carbon sequestration and displacement of carbon emissions from gasoline, of each type of feedstock, (b) examine the optimal allocation of existing cropland for feedstock production, the mix of feedstocks that should be produced and the spatial pattern of land use in the US at various expected prices of gasoline, market prices of carbon emissions, and biofuel subsidy levels, and (c) investigate the optimal plant sizes, transportation patterns and areas to locate bio-refineries.

To achieve the proposed research objectives, we develop a biophysical crop growth model to estimate to yields of dedicated energy crops across the continental US and a dynamic, multi-market equilibrium model, Biofuel and Environmental Policy Analysis Model (BEPAM), to analyze the markets for fuel, biofuel, food/feed crops and livestock for the period 2007-2022. Two perennial grasses, Switchgrass (*Panicum virgatum*) and Miscanthus (*Miscanthus x giganteus*), have been identified in particular as among the best choices for low input bioenergy production in the U.S. (Heaton et al., 2004; Lewandowski et al., 2003). Hereafter, we refer to these as bioenergy crops and to ethanol from any feedstock as biofuel. The feedstocks for biofuels to be investigated here include corn grain, corn stover, switchgrass and miscanthus, and forest residues.

We also develop a supply chain model to examine the cost-effective methods of transportation of feedstock to refineries and the optimal location and size of refineries. We consider biofuels produced not only from corn but also from several cellulosic feedstocks and imported sugarcane ethanol while distinguishing between domestic gasoline supply and gasoline supply from the rest of the world. BEPAM treats each Crop Reporting District (CRD) as a decision making unit where crop yields, costs of crop and livestock production and land availability differ across CRDs. Food and fuel prices are endogenously determined annually and used to update price expectations, cropland acreage and land use choices.

The rest of the report is organized as follows. Section II describes the biophysical crop productivity model and its application. Section III economic simulation model, BEPAM. Section IV describes the transportation model. The three modeling efforts are closely linked with each other, with the biophysical productivity model feeding into the economic analysis that examines areas where it would be profitable to grow energy crops. The results of the economic analysis are then used to examine the locations where it would be optimal to locate refineries. We summarize the major results of the applications of these models in Section V.

II. The Biophysical Crop Productivity Model

We adapted and applied three crop growth models to simulate the yields of miscanthus and switchgrass. These include, MISCANMOD, ALMANAC and ISAM.

Yield Simulations using MISCANMOD

Our work started with the adaptation of well-established crop growth model to a high-resolution modeling system. We began by successfully adapting MISCANMOD (Clifton-Brown, 2000) to a high-resolution (0.1°) grid of the continental United States for both Miscanthus and switchgrass. This process was started by a process to parameterize the model terms for radiation use efficiency, base temperature for accumulation of degree days, LAI growth as a factor of degree days above base temperature, and the light extinction coefficient for each crop. These parameters were calculated based on an examination of the data produced for Urbana, Illinois during the University of Illinois Agriculture Research and Education Centers (UAREC) study of Miscanthus and switchgrass from 2005-2006 (Heaton, 2008). Once we had parameterized the model, we applied it over a 0.1° grid obtained from the University of Oregon PRISM Group dataset interpolated up from the original 4 km scale. In doing so, we have created a continental-wide estimation of peak standing live biomass for both Miscanthus and switchgrass. For the Midwestern US, we have determined an average yield of 40.91 tonnes per hectare with Miscanthus and 14.23 tonnes per hectare with switchgrass. Model results for the Midwest were largely driven by temperature and solar radiation inputs, with water stressing occurring mainly in the western half of the continent and limited yields due to poor senescence occurring mainly in the American South.

Studies based on laboratory freezing tests suggest that miscanthus rhizomes are killed when they are kept at -3°C or below for 3 hours. In order to implement cold temperature effects on Miscanthus yield, we used data from the NASA Global Land Data Assimilation System (Rodell et al., 2004) to modify miscanthus yields to zero at grid points where the 6-hour average soil temperature over the period of 2002-2007 in the 4.5-9 cm soil layer reaches -3°C. In the case of switchgrass, Nobumasa et al. (2002) find that switchgrass rhizomes die if chilled down to -20°C. Since there is no site in the US where the soil temperature could routinely reach this critical temperature, we do not account the cold temperature effect on switchgrass rhizomes. Using the criteria implemented in the model, most of Minnesota, Wisconsin, and the Michigan Upper Peninsula are shown to be very poor performers in miscanthus production, with averaged county-level production being zero for much of this region of the Midwest.

The findings of MISCANMOD based results were published in the *Global Change Biology-Bioenergy* (Jain et al., 2010). The results were also presented at the *ASA-CSSA-SSSA Annual Meetings* (Jain et al., 2009).

Switchgrass Yield Calculations using ALMANAC

Next, we expanded our modeling capability with the ALMANAC model developed by Kiniry, et al (1992). The model was developed as a point system, however, and so we have expanded its capabilities to run against our grid. ALMANAC has a much more detailed growth simulation in comparison to MISCANMOD that will enable us to better understand and project simulated crop yield results, especially with belowground stresses such as water and nutrient stresses. ALMANAC includes more details of the plant growth process and allows us to better understand and project simulated crop yields, especially in the presence of below ground stresses such as water and nutrient stresses.

The location-determined parameters, includes the potential maximum LAI and potential accumulated heat unit (PHU) during growing period (base the base temperature). The potential maximum LAI varies with latitude and seeding rate and thus is given the value from 1 to 3 for different sites. The PHU of each site is validates by calculating the accumulated daily average temperature above base temperature between the planting date and the harvest date. The range of PHU is from 1012.5 ºC to 1578 ºC.

In total 17 sites were chosen to calibrate the switchgrass simulation by ALMANAC model. The range of the sites is from the northeast, Dickinson (46.88N, 102.80E) to the southeast, Beeville (28.40N,97.70E). The model parameters, which were calibrated using the data are either species specific or location specific. The species specific parameters are: (1) Base Temperature for the initiation of switchgrass leaf area growth, (2) Optimum temperature for switchgrass growth, (3) Radiation use efficiency (RUE), Light extinction coefficient, and (4) Optimum nitrogen and phosphorus concentrations. The location specific parameters include: (1) Potential maximum LAI, (2) Potential accumulated heat unit (PHU) during growing period), and (3) Planting date.

The well calibrated model was used to estimate the switchgrass yield from 2000 to 2007 for the entire US. All grids were given 100 ton/ha N fertilizer and 35 ton/ha P fertilizer. No irrigation is applied. The switchgrass in all regions was harvested only once every year. Finally, the average yield for the period 2005 to 2007 was selected to discuss the results.

On a per hectare basis, our model results suggest that the average switchgrass yield for the period 2005-2007 varied between 0 to 21 tons/ha over the entire US. The spatial difference in yield is mainly driven by temperature and precipitation. Higher yield region is located in the central plain and east coast region due to favorable climate conditions in these regions. Low precipitation in the western part of the US restricts the production of switchgrass. Low temperature in the northern region also leads to the low yield due to strong temperature stress on plants growth. Highest yield was simulated in the south of Florida and region along the Gulf of Maxico due to higher organic carbon content in the soil. The simulated results also show strong inter-annual variation in the estimated yield. In the dry year (2005) yield was lower than in the following two years due to strong water stress on switchgrass growth.Higher temperature in 2007 drive higher yield in both north and northeast of the US.

Switchgrass Yield Calculations using Integrated Science Assessment Model (ISAM)

While MISCANMOD and ALMANAC are useful tools to study the potential yields of energy crops, they are unable to account for some necessary dynamic allocation processes of biomass among different vegetation reservoirs. Furthermore, considering the limited number of field campaigns studies and limited numbers of samples for energy crop yields, it is inappropriate to apply these simple models to project the potential yields and study the impacts of environmental factors over the entire US. To overcome these problems, we developed a process-based dynamic bioenergy crop model to explore the productivity of energy crops and their responses to water, climate, and soil stresses at the national scale. The newly developed model is the extended version of the Integrated Science Assessment Model (ISAM) (Jain and Yang 2005; Yang et al, 2009; Jain et al., 2009), which is an entirety of the biophysical, physiological and biogeochemical systems and account for important processes that regulate crop growth such as water, energy within soil-plant-atmosphere system.

The ISAM represents fully prognostic C and N cycles at 0.5 x 0.5 degree resolution, coupled with surface energy and sunlit-shaded photosynthesis schemes (Dai et al., 2003), and soil/snow hydrology (Oleson et al., 2008). The biogeochemistry component of the ISAM accounts for spatial and temporal pattern of forest, and non-forest change cover activities, natural fire regimes, and N deposition, as well as their impacts on plant and soil C and N stocks (Jain and Yang, 2005; Tao and Jain, 2005, Jain et al., 2006; Jain 2007, Jain et al., 2009; Yang et al., 2009). Gross primary Productivity (GPP) is modified through the feedback of N availability on C assimilation, and is obtained by dynamically comparing plant N demand and supply. Net primary productivity (NPP) is calculated based on GPP and autotrophic respiration as calculated based on five above ground vegetation pools (non-woody tree part, above ground woody biomass, tree roots, ground vegetation foliage, and ground vegetation roots.

The carbon assimilation rates under different limitation conditions are calculated by tracing the availability of CO2 fluxes, energy flux and water fluxes for photosynthesis process. All of these fluxes were driven by stomatal conductance calculation. Crop specific carbon and other nutrient allocation among leaf, stem and roots are dynamically calculated by considering the availability of water and light. For example, the model allocates more biomass to roots if there is soil water limitation, but allocates more biomass to leaves and stems if there is light limitation. However, this allocation strategy is further limited by the minimum species-specific root to shoot ratio and structural attribute (Arora and George, 2005). This condition ensures efficient structural carbon to support the growth of leaves.

As a first step, we calibrated and validate the ISAM model simulated switchgrass using 12 sites with 41 effective observed data sets. Chosen study sites represent a large geographic range with different climates, soil types and management practices. According to variation in water and thermal conditions with geographic location, the chosen sites represent four main climate zones for crop growth: cold and dry northern region, warm and dry central region, warm and moist eastern region as well as warmer and moist southern region.

The model requires climate, soil structure and texture information and management practice information as input. Climate data at hourly time scale is interpolated from 3-hourly NCEP reanalysis data, including surface temperature, precipitation, wind, pressure, specific humidity and incoming solar radiation. Soil data are attained from the USDA Web Soil Survey. Management practice information, such as planting and harvest time, tillage information and fertilizer application etc., are obtained from literature survey (Berdahl et al,2005; Fike et al,2006; Henton,2008; Fuentes and Taliaferro, 2002; Sanderson et al,1999). If planting and harvesting time is not available for a specific site, they are calculated from common regional crop operation information compiled by the USDA (USDA, 1997).

To examine ISAM's ability to simulate switchgrass production on the large scale, the simulated mean yield across 13 sites are compared with that of observed values and the model calculated yields are agreed with observed yields for the 13 sites. The regression analysis of the aforementioned sites has a strong correlation coefficient of 0.97, which indicates the model is able to calculate switchgrass production at the US scale.

The national scale simulation of switchgrass potential production shows distinct west to east spatial variability pattern on the US scale. The mean yield of switchgrass through 2002 and 2004 year is as high as more than 8 Mg/ha in the eastern US, gradually decreasing to less than 1 Mg/ha in the region along the western side of the Rocky Mountains. This spatial pattern indicates that the most suitable region for switchgrass energy system development in the US is located in the central and eastern US, especially in the Mississippi and Missouri river plains system and the Great Plains. However, since these regions are also vital agricultural hubs, we must also consider food security and environmental impact before dominating these regions with biofuel crops. Our simulated pattern of switchgrass potential production largely low production in Utah, Nevada and Arizona. However, ISAM simulates lower production in Florida, which is not consistent with our simulation results from ALMANAC. Warm and moist climate of Florida in addition to the sandy soils are detrimental for the production of switchgrass. As such, ISAM more accurately captures the nature of switchgrass growth in Florida.

Switchgrass production distribution patterns in both 2002 and 2004 largely match the precipitation and soil moisture pattern in each year respectively. Less precipitation occurred in 2002, with relative lower accumulated precipitation during the growing season. The year 2004 experienced relatively high accumulated precipitation. Soil moisture largely responds to the precipitation as well as GPP and yield of switchgrass in the eastern US. However, increased precipitation in the western region does not cause a distinct increase in soil moisture, GPP and yield.

The findings of this study will be presented at the 2011 ESA Annual Meeting August 7-12 in Austin, TX.

III. The BEPAM Model

We develop a multi-market, multi-period, price-endogenous, nonlinear mathematical programming model which simulates the US agricultural and fuel sectors and formation of market equilibrium in the commodity markets including trade with the rest of the world. We refer to this model as the Biofuel and Environmental Policy Analysis Model (BEPAM). BEPAM is a dynamic, multi-market equilibrium model, which analyzes the markets for fuel, biofuel, food/feed crops and livestock for an extendable future period (currently set for 2007-2022) in the U.S. This model determines several endogenous variables simultaneously, including vehicle kilometers travelled (VKT), fuel and biofuel consumption, domestic production and imports of oil and imports of sugarcane ethanol, mix of biofuels and the allocation of land among different food and fuel crops and livestock. This is done by maximizing the sum of consumers' and producers' surpluses in the fuel and agricultural sectors subject to various material balances and technological constraints underlying commodity production and consumption within a dynamic framework (McCarl and Spreen, 1980, Takayama and Judge, 1971). This model is designed specifically to analyze the implications of biofuel and climate policies on land use patterns, commodity markets, and the environment.

The agricultural sector in BEPAM includes several conventional crops, livestock and bioenergy crops (crop residues from corn and wheat and perennial grasses, miscanthus and switchgrass) and distinguishes between biofuels produced from corn, sugarcane and cellulosic feedstocks. Crops can be produced using alternative tillage and rotation practices. The model incorporates spatial heterogeneity in crop and livestock production activity, where crop production costs, yields and resource endowments are specified differently for each region and each crop assuming linear (Leontief) production functions. As the spatial decision unit, the model uses the CRDs in each state by assuming an aggregate representative producer who makes planting decisions to maximize the total net returns under the resource availability and production technologies (yields, costs, crop rotation possibilities, etc.) specified for that CRD. The model covers 295 CRDs in 41 of the contiguous U.S. states in five major regions.[1]

The model uses 'historical' and 'synthetic crop mixes' when modeling farms' planting decisions to avoid extreme specialization in regional land use and crop production. The use of historical crop mixes ensures that the model output is consistent with the historically observed planting behaviors (McCarl and Spreen, 1980, Önal and McCarl, 1991). This approach has been used in some existing models also, such as FASOM, to constrain feasible solutions of programming models and generate results which are consistent with farmers' planting history. To accommodate planting new bioenergy crops and unprecedented changes in crop prices in the future FASOM allows crop acreage to deviate 10% from the observed historical mixes. In our model we use synthetic (hypothetical) mixes to offer increased planting flexibility beyond the observed levels and allow land uses that might occur in response to the projected expansion in the biofuels industry and related increases in corn and cellulosic biomass production. Each synthetic mix represents a potential crop pattern generated by using the estimated own and cross price crop acreage elasticities and considering a set of price vectors where crop prices are varied systematically. These elasticities are estimated econometrically using historical, county-specific data on individual crop acreages for the period 1970-2007 as described in Huang and Khanna (2010). Crop yields are assumed to grow over time at an exogenously given trend rate and to be responsive to crop prices.

The model includes five types of land (cropland, idle cropland, cropland pasture, pasture land and forestland pasture) for each CRD. We obtain CRD-specific planted acres for 15 row crops for the period 1977 to 2007 from USDA/NASS (2009) and use this to construct the historical and synthetic mixes of row crops. Cropland availability in each CRD is assumed to change in response to crop prices. The responsiveness of total cropland to crop prices as well as the own and cross-price acreage elasticities for individual crops is obtained from Huang and Khanna (2010). Data on idle cropland, cropland pasture, pasture and forestland pasture for each CRD are also obtained from USDA/NASS (2009). Idle cropland includes land use category for cropland in rotations for soil improvement, and cropland on which no crops were planted for various physical and economic reasons. The estimates of idle land include land enrolled in the CRP which could be an additional source of land available for energy crops. Land in this program is farmland that is retired from crop production and converted to trees, grass, and areas for wildlife cover. We exclude land enrolled in CRP from our simulation model. Cropland pasture is considered as a long-term crop rotation between crops and pasture at varying intervals.

Pasture land consists of land with shrub, brush, all tame and native grasses, legumes and other forage while forestland pasture is stocked by trees of any size and includes a certain percentage of tree cover. Pasture land and forestland pasture are primarily for grazing uses. We keep the level of permanent pastureland and forestland pasture fixed at 2007 levels but allow idle land and cropland pasture to move into cropland and back into an idle state. It can also be used for perennial bioenergy crop production. A change in the composite crop price index triggers a change at the extensive margin and leads to a shift in land from idle cropland and cropland pasture to land available for crop production the following year. The responsiveness of aggregate cropland supply to a lagged composite price index is econometrically estimated and the implications of expanding crop production to idle land and cropland acreage for average yields of conventional crops in each CRD are described in Huang and Khanna (2010). The remaining idle land/pasture land can be used for bioenergy crops. While yields of bioenergy crops are assumed to be the same on marginal land as on regular cropland there is a conversion cost to the use of idle land/cropland pasture for bioenergy crop production. In the absence of an empirically based estimate of the ease of conversion of marginal land for perennial grass production we assume a CRD-specific conversion cost equal to the returns the land would obtain from producing the least profitable annual crop in the CRD. This ensures consistency with the underlying assumption of equilibrium in the land market, in which all land with non-negative profits from annual crop production is utilized for annual crop production. As annual crop prices increase, the cost of conversion increases; the "supply curve" for idle marginal land is, therefore, upward sloping. We impose a limit of 25% on the amount of land in a CRD that can be converted to perennial grasses due to concerns about the impact of monocultures of perennial grasses on biodiversity or sub-surface water flows. We examine the sensitivity of model results to this assumption by lowering this limit to 10%.

The perennial nature of the energy crops included in the model requires a multi-year consideration when determining producers' land allocation decisions in any given year. For this, we use a rolling horizon approach where for each year of the period 2007-2022 the model determines production decisions and the corresponding dynamic market equilibrium for a planning period of 10 years starting with the year under consideration. After each run, the first year production decisions and the associated market equilibrium are used to update some of the model parameters (such as the composite crop price index, land supplies in each region and crop yields per acre for major crops), based on previously generated endogenous prices, and the model is run again for another 10-year period starting with the subsequent year.

The behavior of agricultural consumers' behavior is characterized by linear demand functions which are specified for individual commodities, including crop and livestock products, In the crop and livestock markets, primary crop and livestock commodities are consumed either domestically or traded with the rest of the world (exported or imported), processed, or directly fed to various animal categories. Export demands and import supplies are incorporated by using linear demand/supply functions. The commodity demand functions and export demand functions for tradable row crops and processed commodities are shifted upward over time at exogenously specified rates. The crop and livestock sectors are linked to each other through the supply and use of feed items and also through the competition for land (because the grazing land needed by the livestock sector has alternative uses in crop production).

The biofuel sector distinguishes biofuels produced from corn, sugarcane ethanol and cellulosic feedstock with all biofuels being perfect substitutes for each other. Biofuel from sugarcane is imported from Brazil and CBI countries subject to policies described above. Gasoline is produced domestically as well as imported from the rest of the world. The demand for gasoline and biofuels is derived from the demand for VKT. We assume a linear demand for VKT as a function of the cost per kilometer and that VKT is produced using a blend of gasoline and biofuels. At the individual consumer level (with a conventional vehicle), the two fuels are currently perfectly substitutable in energy equivalent units up to a 10% blend. For an individual consumer with a flex fuel car the two fuels are substitutable up to an 85% blend. At the aggregate level, we consider a representative consumer that owns a vehicle fleet that consists of a mix of the two types of vehicles; in 2007, only 2.9% of vehicles in 2007 were flex-fuel vehicles (EIA, 2010). The ability to substitute gasoline for biofuels at the aggregate level is, therefore, limited by the mix of vehicles. It is also limited by the available ethanol distribution network and infrastructure for retail ethanol sales. We, therefore, consider gasoline and biofuel to be imperfectly substitutable at the aggregate level and use a constant elasticity of substitution function to model the aggregate blend of fuel produced. The VKT demand function and CES production function are calibrated for the base year assuming a specific value for the elasticity of substitution between gasoline and ethanol and observed base year prices and quantities of these fuels and VKT. We examine the implications of varying the extent of substitutability on the consumption of the two types of fuels and on the agricultural and fuel sectors. The demand for VKT is shifted upwards over time and the VKT consumed is determined by the marginal cost of kilometers which in turn depends on the marginal costs of gasoline and biofuels. The shares of various fuels are determined endogenously based on fuel prices.

In the presence of the RFS, the quantity mandate imposes a fixed cost of biofuel on blenders. The average cost of the blended fuel (gasoline and ethanol) will fall as the level of gasoline consumption increases, but the average cost will be greater than marginal costs for low levels of gasoline consumption. Thus, at low levels of fuel consumption blenders can be expected to price fuel based on its average cost (if average cost is greater than the marginal cost) in order to avoid negative profits. In this case VKT will be determined by the average cost of a kilometer rather than its marginal cost. If gasoline consumption is high enough (or if biofuel consumption is small) it could be profitable to use marginal cost pricing of the blended fuel. The model selects the appropriate rule for pricing the blended fuel depending on whether average cost of VKT is greater or smaller than its marginal cost.

The endogenous variables determined by the model include: (1) commodity prices; (2) production, consumption, export and import quantities of crop and livestock commodities; (3) land allocations and choice of practices for producing row crops and perennial crops (namely, rotation, tillage and irrigation options) for each year of the 2017-2022 planning horizon and for each CRD and (4) the annual mix of feedstocks for biofuel production, domestic production and imports of gasoline and consumption of VKT.

IV. Location and Capacity of Refineries: the Transportation Model

Under this task, we develop a model to find the optimal bioenergy supply chain, namely the optimum feedstock production, delivery, processing and biofuel distribution network, locations and capacities of corn and cellulosic biorefineries. Previously, in our modeling system the feedstock supply pattern was determined by the economic equilibrium model based on the regional resource (land) availabilities, production costs and crop yields only, disregarding the transportation costs of both feedstocks and biofuels. We now incorporate the latter and integrate the bioenergy feedstock production and refining/processing components in a unified framework. This issue was listed among the future tasks in our previous progress report and it is accomplished over the past year by coupling the economic equilibrium model with the facility location/transshipment model.

Knowing the possible spatial layout of the future biorefinery industry is important for two reasons. First, this will provide valuable insight to entrepreneurs who will be investing in the biofuel processing industry, particularly in cellulosic biomass processing plants which currently do not exist. Second, the two-way linkages between the locations of biorefineries and regional distribution of feedstock supply must be taken into account when determining both since the regional feedstock supply pattern affects where to build biorefineries and in turn the locations of biorefineries affect the regional supply potential. Ideally the locations of bioenergy feedstock production areas and the processing plants should be determined simultaneously. However, this is computationally impossible due to the very large size of our sector model and nonlinearities included in its objective function (consumers' surplus). As a practical alternative, we use a two-step sequential procedure (described below) to determine an approximately optimum solution.

We first determine the optimum bioenergy feedstock supply pattern by the economic equilibrium model considering the regional land availabilities, production costs and crop yields and disregarding the transportation costs of both feedstocks and biofuels, as before. Based on this first round solution of the sector model, we determine the optimum biorefinery locations, timing and capacities. We then feedback this information and solve the economic equilibrium model again to revise the optimum supply response now considering the processing locations and feedstock delivery costs also. After the second round solution some regions that may have slight advantage over other regions, due to their lower production costs and/or higher yields in the first round solution, may lose their comparative advantage if they are too far away from the processing plants. The end result of this approach will represent a spatially coherent supply pattern and processing/delivery network. Empirical tests with a computationally tractable smaller version of the model showed that the results of the sequential approach were extremely close to the true optimum solution (where we linearized the nonlinear consumer surplus terms in the sector model -using separable programming techniques- and solved the supply response and facility location variables simultaneously using linear integer programming).

As mentioned in our previous reports, for a given feedstock supply pattern finding the optimum facility location and trans-shipment network requires a large scale discrete optimization model including binary (yes/no type) decision variables. Solving this model is proven to be difficult because of the large number of binary variables involved (every county is considered both as a potential source of feedstock supply and a location for a future biorefinery). Modeling even a single year in isolation from the rest of the planning horizon (2007-2022) requires hundreds of binary variables and thousands of feedstock and biofuel delivery variables. A one-year model is computationally tractable, but in order to impose continuity in biorefinery operations we have to consider the entire planning horizon together where year to year dynamics of building, retaining or expanding biorefineries are simulated. This is necessary to rule out the possibility of building a refinery in one year, retiring it next year and then bringing it back into the solution in a later year just because it is optimal to do so based on the dynamic feedstock supply response obtained from the economic model. Such an erratic processing infrastructure cannot happen in reality. Solving the problem for the entire planning horizon by use of mixed integer programming is computationally impossible, however. Our previous attempts to solve this problem using a heuristic approach (Lagrangian relaxation) was not fruitful. To cope with this computational difficulty, we have developed a stepwise and backward recursive modeling procedure as in dynamic programming. This procedure is described briefly below.

We start with the last year of the planning horizon and solve the optimum facility locations and capacities that are consistent with the bioenergy supply pattern for that year (obtained from the agricultural sector model). As mentioned earlier, this problem is computationally tractable. Using this information we go backward and solve the problem for the previous year, again considering a one-year model and the feedstock supply for that year, but this time incorporating the processing facility infrastructure information for the subsequent year (obtained in the previous solution). More precisely, if a plant is built with some optimum capacity at a potential biorefinery location in the previous solution, we allow that location to be in the solution of the current year also, with the same or a lower capacity. Thus, a plant may or may not exist at that location in the current year, and the 'same or lower' capacity restriction allows the possibility of capacity expansion in the subsequent year. We apply this to both corn ethanol and cellulosic ethanol plants. If a particular location has not been selected for building a cellulosic refinery in the previous solution we exclude the possibility of building a cellulosic plant at that location in the current year. This implies that once built all cellulosic plants will continue to operate in the subsequent years with the same or higher processing capacities, which is a reasonable assumption since cellulosic ethanol demand increases continuously over time (due to RFS mandates). For corn ethanol plants we allow a plant to exist at a given location even if the last year's solution does not have a refinery at that location. This allows retiring some old and spatially disadvantaged corn ethanol plants. After solving the problem for the second year from the last, we go backward again and solve a similar problem for the previous year, and use this procedure iteratively until solving the first year of the planning horizon. For the first year we fix the known locations and capacities of the existing corn ethanol plants.

We applied this approach successfully and solved the facility location/transshipment problem for the entire planning horizon using the first-round solution of the economic model solution as input data. We then used the optimum processing infrastructure information as a feedback and solved the economic model again after adding a transshipment component where different types of bioenergy feedstocks produced in each supply region can be shipped to a nearby biorefinery location and the biofuel produced at each processing plant can be shipped to a nearby blending facility. Both the feedstock/biofuel production and delivery decisions are now determined simultaneously consolidating these two interdependent activities. As expected, the feedstock production regions determined in the second round solution of the sector model, which were somewhat scattered in the first round solution, are clustered around the processing facilities. This results in a more compact and spatially coherent biofuels industry which represents a more realistic solution.

V. Major Results

We use the BEPAM model to develop supply curves for cellulosic feedstocks under various biomass prices ranging from $20/MT to $140/ MT in $10 intervals under various assumptions (Khanna et al., 2011b). Biomass production is found to be viable at about $30-40/MT (mainly switchgrass and corn stover). With high costs of production, large scale production only becomes viable at a price of $50/MT. The amount of production varies considerably depending on production assumptions, ranging 0.3-406 MMT at $40/MT. At a price of $140/MT, maximum production of biomass ranges 617-923 MMT. Perlack et al. (2005) estimated that 623 MMT is available from perennial grasses and crop residues under an optimistic scenario of productivity growth and availability of perennial grasses. Our analysis shows that this quantity could be available at a price of about $60-70/MT but could require a price higher than $140/MT under less optimistic cost conditions, particularly for a high yielding grass like miscanthus.

We find that the supply curves for biomass from switchgrass and wheat straw are fairly steep, and together these feedstocks provide less than 10% even at a high biomass price under pessimistic production conditions for biomass. When the production conditions are optimistic, switchgrass production is much higher even at relatively low biomass prices; however, the supply curve for switchgrass is backward bending because switchgrass competes with miscanthus for land and is much more competitive with miscanthus at low biomass prices than at high biomass prices. As biomass price increases, the relatively higher yields of miscanthus compared to switchgrass result in much higher returns per hectare on land under miscanthus and therefore land allocated to miscanthus increases while that under switchgrass decreases.

We then examine the effects of various policy scenarios on the agricultural and fuel sectors, such as the Renewable Fuel Standard, volumetric tax credits, subsidy programs such as the Biomas Crop Assistance Program and carbon price policies. The detailed results of this research on the impact of these policies on allocation of cropland, production and prices of key crop and livestock commodities and fuels, and social welfare are reported in various publications such as Khanna et al. (2011a and b) and Chen et al. (2010). We summarize the major findings as follows.

We find that under the RFS, corn ethanol would be produced at its maximum allowable level of 56 B liters from 2015 and beyond, corn ethanol could constitute a maximum of two-thirds of the cumulative biofuel production over 2007–2022, with the remaining being met by advanced biofuels at the mandated minimum level. Given the assumptions about the rate of decline in costs of producing advanced biofuels from cellulosic feedstocks in the US and sugarcane ethanol in Brazil as described above, we find that the RFS would lead to the production of about 613 B liters of corn ethanol (instead of the maximum allowable level 801 B liters) and 608 B liters of advanced biofuels including 38 B liters of sugarcane ethanol imports over the 2007–2022 period. This would increase the cumulative production of corn ethanol by 107% relative to the business as usual (BAU) scenario over this period. The cellulosic biofuels are largely produced using miscanthus (49%) and forest residues (22%), with the rest being produced using switchgrass, corn stover and wheat straw. The RFS would also increase in the volumetric share of ethanol in total fuel consumption to 21% in 2022.

The RFS leads to an increase in total cropland by 6% (6.9 M ha), most of which is due to increased corn production to produce the additional corn ethanol. Land under corn in 2022 increases by 16% (about 4.7 M ha) compared to the land requirement in the absence of the RFS. With a high yielding grass like miscanthus, planting only 4.4 M ha of miscanthus and 3 M ha of switchgrass would be sufficient to produce the required amount of cellulosic biofuels. Of this 7.4 M ha under bioenergy crops only 0.4 M ha is converted from cropland and about 7M ha is from currently idle cropland or cropland pasture. Thus, a total 12.1 M ha is required for biofuel production, of which about 5 M ha is converted from acreage previously under other crops (including soybeans, wheat, rice, cotton and pasture), accounting for 4% of the 121.5 M ha of cropland in 2007 and the remaining 7.1 M ha is obtained from changes at the extensive margin. Corn stover and wheat straw would be harvested from 10% and 5% of the land under corn and wheat, respectively, in 2022.

We find that the mix of cellulosic feedstocks differs considerably across regions. Corn stover is harvested mainly in the Plain States (Kansas, Nebraska, North Dakota, and South Dakota) in 2022 while 80% of wheat straw acreage is collected in the Western States (including Arizona, California, Idaho, Oregon, and Utah). About half of the switchgrass acreage in 2022 is in Texas and 15% is in Missouri. Miscanthus is more competitive than switchgrass in terms of break-even costs of production, and its production is fairly concentrated in the Great Plains (Oklahoma), and in the Midwest and along lower reaches of the Mississippi river.

We find that the provision of subsidies such as those under BCAP and the volumetric tax credits have the potential to significantly change the mix of biofuels and make cellulosic ethanol competitive with corn ethanol and sugarcane ethanol. This reduces the total cropland needed to meet the RFS and by reducing demand for corn ethanol it reduces the pressure on crop prices.

We also analyze the implications of the RFS with a carbon price instrument. We find that as compared to the RFS alone, the addition of a $30 per metric ton price on CO2e lowers the cumulative volume of corn ethanol produced and raises the volume of biofuels from miscanthus and corn stover, accordingly. The total GHG emission decreases by 3% as compared to the RFS alone since the carbon price raises the cost of VKT and hence lowers VKT. The total gasoline consumption falls by 1.5% under this scenario as compared to the RFS alone and is 3% below the level with the RFS and biofuel subsidies. The total land requirement to meet crop and fuel production needs is marginally lower than that under the RFS alone, mainly due to lower corn ethanol production. It is also slightly lower than that with the biofuel subsidies, due to the lower cellulosic ethanol production. The crop and livestock prices are lower than those under an RFS alone and higher than those in the scenario with the biofuel subsidies.

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[1] Western region includes Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington and Wyoming; Plains includes Nebraska, North Dakota, Oklahoma, South Dakota, Texas and Kansas; Midwest includes Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio and Wisconsin; South includes Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi and South Carolina; Atlantic includes Kentucky, Maryland, New Jersey, New York, North Carolina, Pennsylvania, Tennessee, Virginia, and West Virginia.